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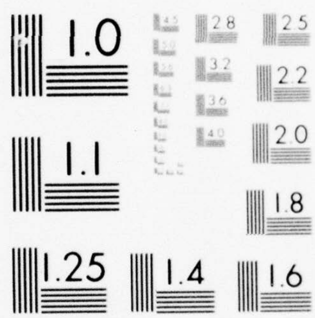

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DEVELOPMENT OF A SPILLED OIL RECOVERY SEPARATOR FOR USE AS PART OF AN OIL SPILL REMOVAL DEVICE

Andrew Harvey
William Mack
Richard Stevenson
Adi Guzdar

October, 1977

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16. Abstract

This report describes the development of an oil-water separator for use with oil spill clean-up equipment. The development is an extension of technology used previously in designing oil-water separation devices for cleaning bilge and ballast discharge waters. A new design was needed to meet the different flow rate, separation performance, head and suction capability, oil type, and oil inlet concentration requirements. A prototype centrifugal, axial flow separator with a nominal fluid throughput of 100 gpm was developed. This report details the design, fabrication, testing and control of the unit.

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METRIC CONVERSION FACTORS

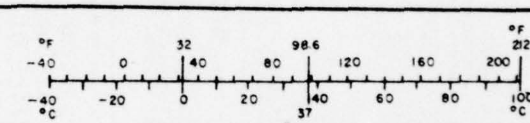
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. INTRODUCTION

The U.S. Coast Guard is charged with the responsibility of oil spill cleanup from the nation's navigable waterways. As part of their effort in this area, the U.S. Coast Guard has been developing a number of devices designed to pick up oil from the surface of the water. Many of these devices work well in calm conditions, but when faced with fast currents or waves, their performance deteriorates. Coast Guard testing of pickup devices indicates that the recovered oil typically contains 30 to 80 percent water. Temporary storage of this quality oil is very inefficient and necessitates either much larger storage capacity or more frequent trips to the supporting shore facility to empty the storage tanks. A significant improvement in equipment and time utilization could be realized if the oil stored contained very little water.

Consequently, Foster-Miller Associates, Inc. (FMA) undertook, under U.S. Coast Guard Contract No. DOT-CG-53272-A, the development of an oil water separator for use as part of an oil spill pickup device. FMA had been involved in the development, under Coast Guard direction, of oil-water separation devices for use in cleaning bilge and ballast discharge waters. It appeared that the technology could be used to develop a compact centrifugal machine that would both pump and separate oil water mixtures typically encountered in spill recovery at sea.

The first two machines designed and tested for bilge applications were novel axial flow centrifuges having three stages in one rotor. The first and third stages were basically sheet metal vanes for collecting large drops or free oil, and the intermediate stage was a wrapped cylinder of sheet metal for collecting and coalescing finely dispersed or emulsified oil.

The coalescing centrifuge has been shown to have high separation efficiency, relatively high flow capacity, and very low power requirement, but limited oil handling capability.

Consequently, a third machine was designed and tested as a primary separator and pump for the system that was based upon the centrifuge.

The original pump/separator was a novel design for continuous discharge of oil, water, and solids is slurry form. It consisted of a rotating bowl filled with vanes similar to the previous centrifuge. The rotor spun submerged in a liquid filled housing, close-coupled by shaft and mounting to an electric motor. The test model showed insufficient flow capabilities due to its ultra-compact configuration, excessive power due to the wetted bowl outer surface, and internal phase separation or sealing difficulties. However, it proved the concept of pumping while separating, and automatic control using simple pilot flow valves was demonstrated.

In addition to work on oil-water separation, testing was conducted to determine the emulsifying characteristics of various types of pumps. This data can be used to evaluate the separation requirements for oil-water mixtures that have been pumped, such as in transfer from skimmer to vessel.

The contracts and reports for all of this developmental work are cited in the Bibliography (Section 9). Reviewing this work on bilge water systems, the Coast Guard saw that our technology might be applicable to a different mission, oil-spill response, but that the design specifications or goals should be different.

The differences between bilge system performance and spill recovery separator goals were in several factors; flow rate, separation performance, head and suction capability, and the range of input oil concentration and type. This is shown in Table 1.

Table 1-1. Comparison of FMA Separator Specifications

Specification	Centrifuge	Separating Pump	Spilled Oil Separator
Flow Rate	50 gpm	50 gpm	100 gpm
Input Oil/Water	0 to 2%	0 to 20%	10 to 90%
Output Oil/Water	10 ppm	1%	N.A.
Oil Recovery	N.A.	N.A.	95%
Head Rise	None	30 psi	>30 psi
Suction Lift	None	Some	Maximum
Oil Types	No.2, Lube	No.2, Lube	Light to Heavy

This comparison shows that the spilled oil separator was to be both a combination and an extension of the previous technology. In addition, it was recognized that the control system for the spilled oil separator would have to control both oil and water discharges, which was not necessary for the bilge equipment. For expedience, previous design methods, control methods, and some components were to be used.

In general, the design configuration that was proposed and subsequently developed for spilled oil can be described as follows:

a. Oil-water separation takes place in axial flow in a long tubular rotor spinning in a ventilated housing, similar to the centrifuge. This offers maximum flow and separation capability for minimum power. It also incorporates a frame-mounted design with bearings, seals, and drive most suitable for the application.

b. The tubular rotor is packed only with bent sheet metal vanes, similar to the separating pump, with no coalescer sheet wrap. This permits high flow of heavy viscous oil, which would cause prohibitive

pressure loss in a typical coalescer. Such coalescing is not required to meet the oil-water separation goals.

c. The inlet and discharge ends are similar to the separating pump, except enlarged to give higher flow, head, and suction capabilities. Flow controls on the water and oil discharges are the same as that used on the separating pump oil discharge.

This configuration is a logical stepping-stone from proven technology. It is suitable for field tests, optimization, and scale up, as the application requirements become more clear.

This Spilled Oil Recovery Separator, as it is called, will have two possible operating modes.

a. <u>Spill Removal Device Mounting</u>

In this mode, the separator is mounted directly on the oil spill removal device with the inlet fed directly with the recovered oil-water mixture. The separator, providing its own suction, is to process the mixture and pump the recovered oil to the temporary storage tank remotely located in the accompanying tender vessel. The water is to be discharged directly into the sea ahead of the pickup device.

b. <u>Storage Vessel Mounting</u>

In this mode, the separator is remotely located on the accompanying tender vessel. The inlet oil-water mixture is obtained through a hose connection to the pickup device. The maximum remote location of the separator is determined by the suction capabilities of the separator. The separated oil is

again discharged to a nearby temporary storage tank and the water is discharged overboard.

For either mode, the design goals of the separator were as follows:

a. 100 gpm total throughput flow rate,

b. Input oil concentrations ranging from 10 to 90 percent oil in water.

c. Discharged water concentration of 95 percent water,

d. Discharged oil concentration of 90 percent oil,

e. Operation on a wide range of oil types.

This report documents the effort undertaken by FMA in designing, fabricating and testing the Spilled Oil Recovery Separator. Section 2 discusses the design and control of the Spilled Oil Recovery Separator. Section 3 describes the test loop used for the testing. The fluid mechanical performance of the separator is presented in Section 4 and the separation performance in Section 5. The conclusion of the authors are presented in Section 6, and Section 7 presents their recommendations.

2. DESIGN OF THE FMA SPILLED OIL RECOVERY SEPARATOR

The separator designed by FMA to meet the requirements of a spilled oil recovery separator is pictured in Figure 2-1 and is shown pictorially in Figure 2-2. A reduced size assembly drawing is shown in Figure 2-3. This separator is a combination of various design features of two separators previously developed by FMA, the FMA Separating Pump and the FMA Centrifugal Coalescer.

The mechanical design of the spilled oil recovery separator and the method of effluent discharge control are discussed below.

2.1 Mechanical Design

An assembly drawing of the FMA Spilled Oil Recovery Separator is shown in Figure 2-3. This shows basically a tubular housing with end pieces containing commercial bearings and face seals. Between the latter, the tubular rotor is straddle-mounted and spins in a ventilated housing. The main shell of the rotor is 8 inch pipe. Inside this shell, for a length of 12 inches, axial flow and oil-water separation takes place. Outboard of this 8 by 12 inch rotor section are intake and discharge sections. The flow paths of oil and water are shown in Figure 2-2.

The flow path of the process stream is basically axial in a tubular rotor shell. The flow is introduced through an axial inlet housing containing a cruciform vortex breaker and passes through a 24 vane inlet rotor which starts bringing the liquid up to rotational speed. Following the inlet rotor, the liquid flows radially outward guided by 48 cast radial pumping vanes. Following these vanes, the liquid passes under a dam and resumes axial flow in the annular rotor section where the actual separation takes place. In this section, the flow is guided by 120 axial

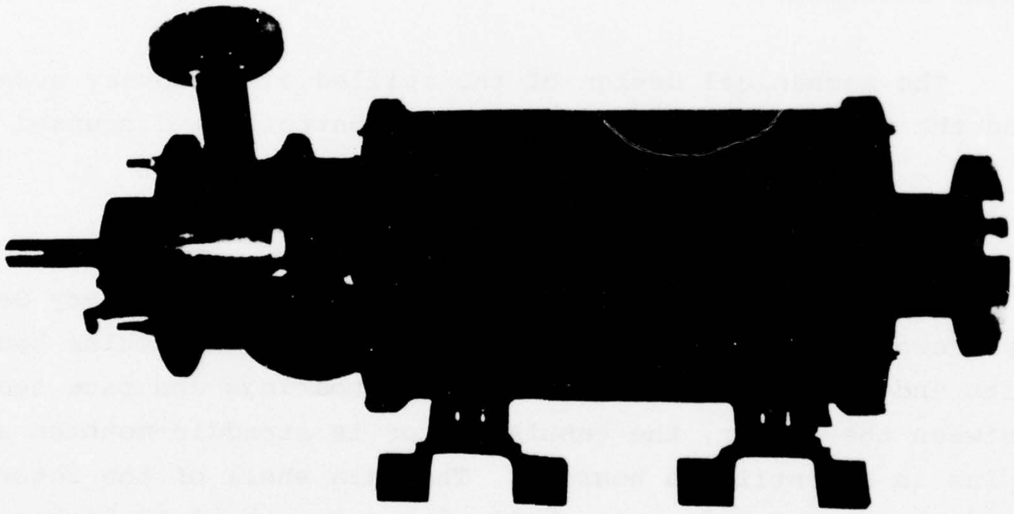


Figure 2-1. Photograph of the FMA Spilled Oil Recovery Separator

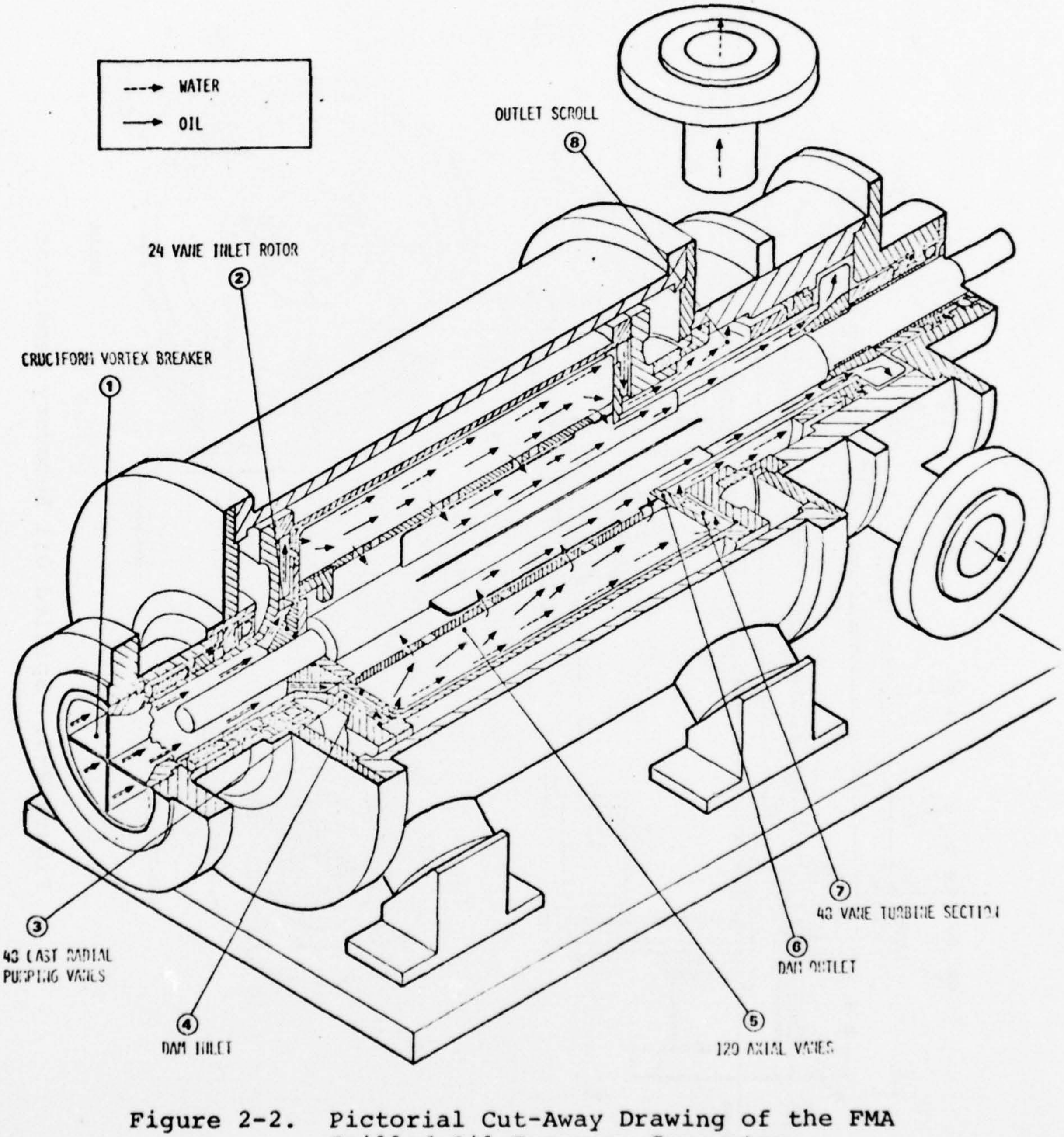


Figure 2-2. Pictorial Cut-Away Drawing of the FMA Spilled Oil Recovery Separator

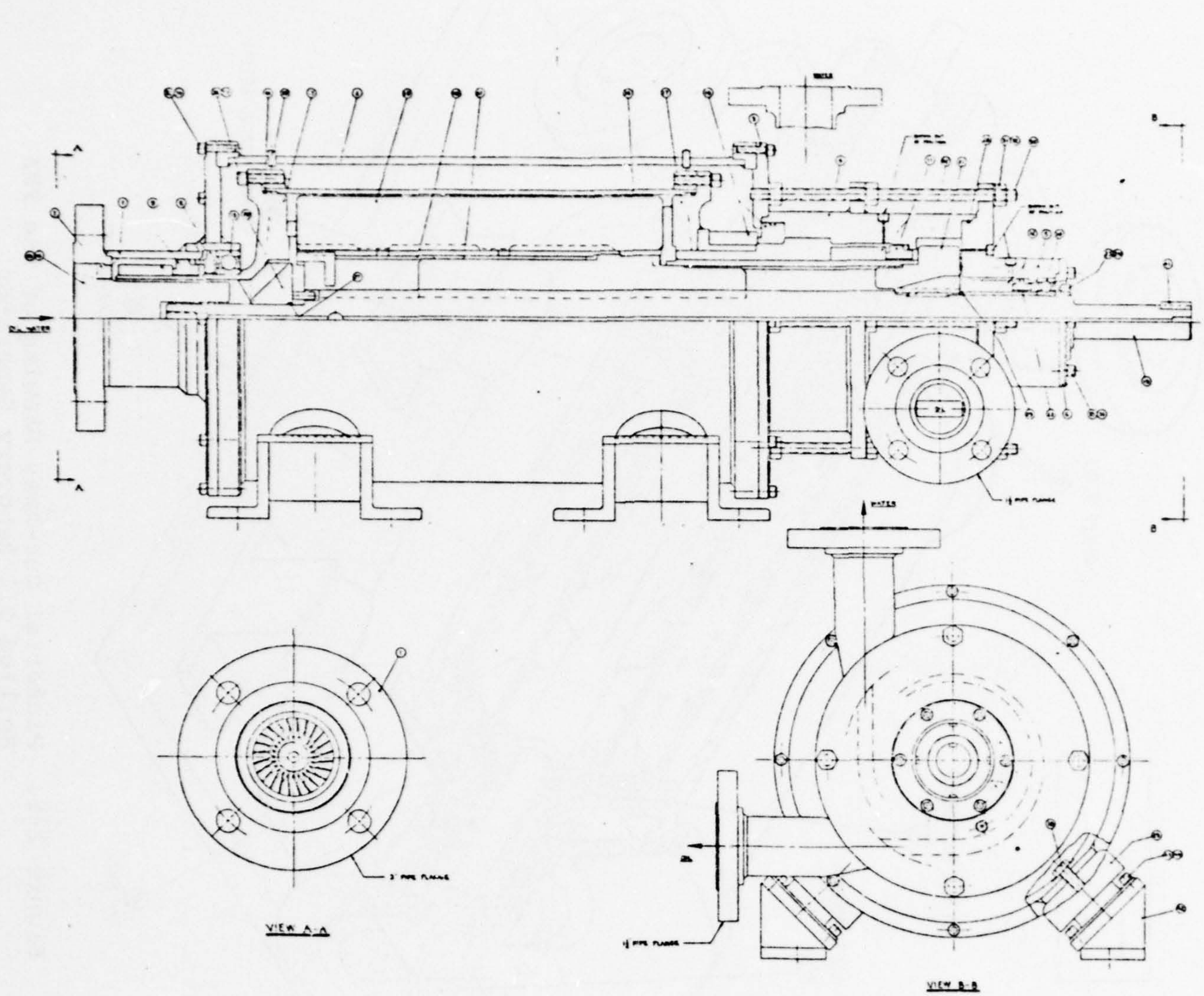
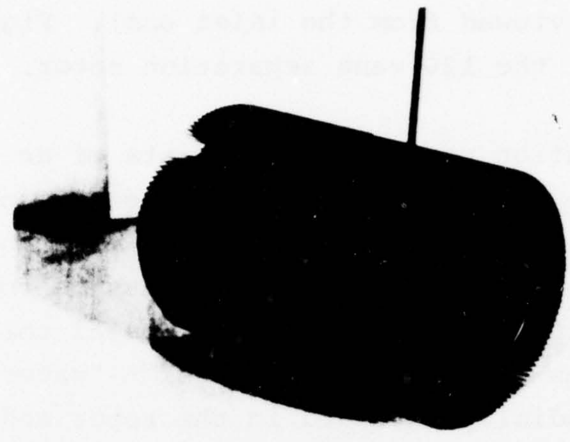


Figure 2-3. Spilled Oil Recovery Separator

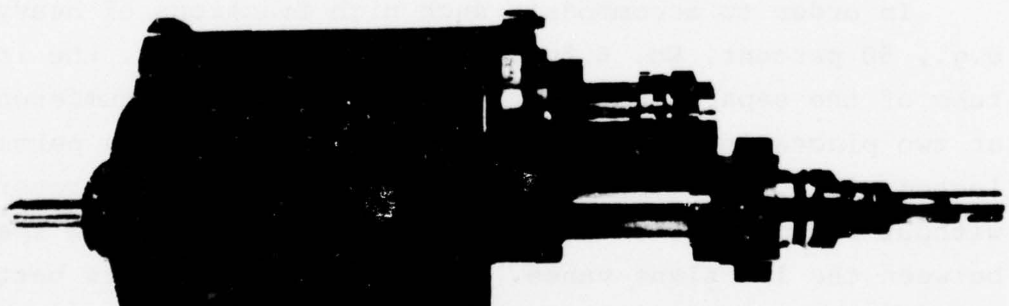
vanes, which are slanted in the direction of rotation (counter-clockwise when viewed from the inlet end). Figure 2-4 presents a photograph of the 120 vane separation rotor.

The separation rotor piece consists of an inner tubular pipe section and the 120 slant vanes that are permanently bonded to it, in axial slots. The vanes overhang the tube about 1 inch at the far downstream end, which provides a passage for oil, lighter than water, to "overflow" into the central axial core of the rotor. Water discharges through an annular slot "under" a ring-shaped dam farthest radially outboard in the rotor end piece. In this fashion the oil and water flow coaxially the entire length of the slant-vane filled section of the rotor. This allows for maximum separation and consolidation of the oil phase while not permitting any circulatory currents. This is best for light, inviscid oil. Unfortunately, this configuration presents high resistance to the axial flow of dense, viscous oil in large concentration. (Detailed analysis of flow on and through slant vanes is given in Reference 1.)

In order to accommodate such high fractions of heavy oil, e.g., 50 percent, No. 6 fuel oil at 60^{O}F in water, the inner tube of the separation rotor piece is slotted circumferentially at two places intermediate in the axial span. This permits collected oil to drain directly radially inward to the rotor core without flowing the entire axial length of the narrow spaces between the 120 slant vanes. This apparently offers better performance in this situation, but if the intermediate oil drain slots are open with low oil concentrations or light oil, then flow can circulate in and out of the different slots and spoil separation performance. For this reason, the slots can be preferentially covered by the insertion of simple tubes or hoops inside the separation piece. It is expected that selectively the proper slot openings can be covered depending on the particular spill recovery situation, i.e., the oil type and skimmer performance.



a. 120 Slant Vane Separator Rotor



b. Rotor Housing and Assembled Rotor Internal Parts

Figure 2-4. Photographs of Spilled Oil Recovery Separator Parts

The separated water passes out under a dam and flows radially inward guided by a 48 vane turbine section. The water then passes through an annular space and is discharged from the separator via an outlet scroll.

The oil which is separated from the process stream in the slant vane section is guided radially inward by these vanes and passes into the hollow rotor core surrounding the shaft. In this core, it flows axially and enters an 8 vane oil pumping rotor which discharges the separated oil via an outlet scroll.

Air separated from the process stream migrates into the hollow core surrounding the shaft and is discharged via a centerline hole running the length of the shaft and a rotary coupling.

The entire rotor is constrained to spin as one unit on two standard commercial sealed bearings located at the inlet and outlet ends of the separator. The rotor spins in air and is totally contained within a stationary housing. The rotor housing and assembled rotor internals are shown in Figure 2-4.

Four commercially available mechanical face seals are utilized within the separator. These seals employ tungsten carbide and bronze for the seal faces.

All wetted parts of the Spilled Oil Recovery Separator are constructed of Navy M bronze or 316 stainless steel.

2.2 Effluent Discharge Control

Because of the wide range of possible oil inlet concentrations, the greatest technical development effort was required in the area of effluent discharge control. The wide range of inlet concentrations combined with the possibility of rapid and unpredictable changes in the inlet concentration required that the effluent

discharge streams be controlled automatically. It is obvious that even if the oil-water separation in the rotor is perfect, the separate discharges must be at the correct rate to obtain each phase uncontaminated by the other. In all centrifugal and gravity separation devices, control depends on maintaining an interface surface or "level" in the separation zone. Some use level sensing devices. Most centrifuges operate with unrestricted spillage of the minor phase over a dam ring. Some have pitot-type pumps to scoop off one or both phases, the amount scooped off being dependent on the internal interface level and, hence, the phase levels under and over the internal dam. This is quite suitable for typical process centrifuges that have large diameters relative to their flow rate and usually have rather constant operating conditions for which the devices are adjusted.

Due to the compact size of the device and the wide inlet concentration range, none of the common methods of separator discharge control would work. For this reason, it was decided to employ and expand the discharge control scheme developed previously by FMA for use on the FMA Separating Pump and FMA Centrifugal Coalescer (Reference 2).

The expansion of the previous control method currently is simply to use larger flow valves and a separate control on both oil and water. (Previously only oil flow was controlled.) This was expedient, although we recognized that an integrated, specialized oil-water control was desirable.

The control scheme is based upon maintaining a nearly constant radial position of the annular oil-water interface in the rotor. The radial increase in static pressure in this two-phase "pool" is balanced by the static pressure gradients in separate discharge paths for oil and water in the rotor. Dynamic pressures and pressure losses are relatively small in these zones, so the rotor's oil-water pool and its separate discharge paths

represent opposite "legs" of a manometer in the rotational "gravity" field. If the level of oil in the pool changes it causes a change in pressure in each discharge leg. These pressures need not be measured in the rotating parts, but may be closely approximated using typical static-pressure wall-taps near the rotor discharges, upstream of any diffusion of the discharge swirl velocity.

The manometric principle just described can be used rather directly to estimate the differential pressure change between oil and water taps with any change of rotor pool level. For example, if the oil is nine-tenths of the density of the water and the pool of oil "fills" from a radius of 2 inches to a radius of 3.5 inches, the oil-water differential pressure changes about 5 psi, oil pressure increasing relative to water pressure. This *change* in differential pressure is *not* dependent on the initial or set-point value of the differential pressure. This set-point value of the differential depends on the *desired* radial level of the oil pool, the radial positions of the oil and water taps, the difference in fluid densities, and other minor variables such as rotor-housing passage design and flow effects that are difficult to predict.

We tested several control pressure tap locations to confirm theory, investigate minor variables, and to select the most convenient differential pressure for the particular set of controls.

A schematic of the control system used for this initial development is shown in Figure 2-5. When the differential control pressure between oil and water changes from the desired set point, it causes a force *change* in both pilot valves. Within the particular control range of each pilot, this causes a bleed flow change. Within the control range of each discharge flow control valve, a change in its pilot bleed flow causes a change in discharge flow, oil or water, respectively. The differential pressure ranges for flow control of oil and water can overlap,

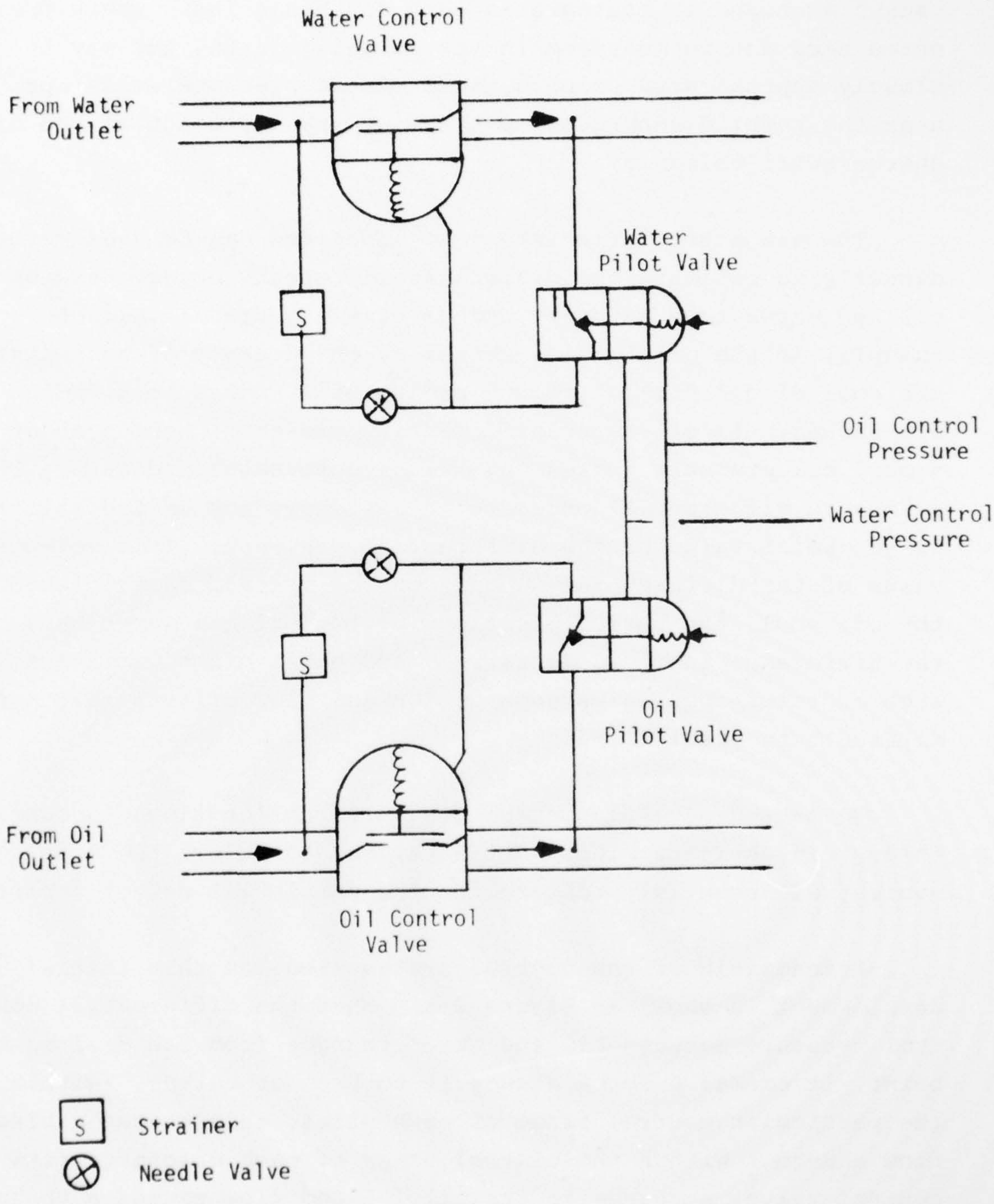


Figure 2-5. Schematic Diagram of Automatic Effluent Discharge Control System

or they can be separate, so that first the oil valve opens full and then the water valve starts to shut, and *vice versa*. Overlapping control appears better for maintaining constant total flow rate, but this is "touchy" with the current system, which has mechanically separate valves. The range and speed of operation of each pilot-valve-control-valve unit is determined by the spring rate and set position in the pilot as well as the needle valve setting in the pilot bleed path.

In general, this type of flow control is able to swing from shut to fully open in one second or less with a control pressure change of 1 psi or less. The primary advantage of the control system is that it uses process liquids and no external power.

3. SPILLED OIL RECOVERY SEPARATOR TEST LOOP

The flow loop used to perform the testing of the Spilled Oil Recovery Separator is shown schematically in Figure 3-1. This test loop is capable of supplying the separator with oil/water mixture at flow rates up to 150 gpm. The input mixtures can be varied from 100 percent oil to 100 percent water.

The oil in the input mixture is kept in a 2000 gallon supply tank. From this tank, the oil may be supplied to the separator at a metered rate by either one of two positive displacement pumps or through a direct suction line. One of these positive displacement pumps is driven by a variable speed DC motor.

The water in the input mixture is also kept in a 2000 gallon supply tank. From the tank, the water may be supplied to the separator at a metered rate by a positive displacement pump driven by a variable speed motor, by a centrifugal pump, or through a suction line.

The oil and water in the input mixture are mixed together in a pipe tee from which they pass through a strainer and a sight glass and then into the separator.

Outlet flow lines connect to the oil and water outlets of the separator. The oil outlet line passes through a positive displacement flow meter and a sight glass and then returns to the oil supply tank. The water outlet line passes through a sight glass and a flow meter and then returns to the water supply tank. Provisions are available during all-water tests to return the liquid in the oil outlet line to the water tank.

Sample taps are located at the inlet to the separator and at both separator outlets. Sample taps consist of 1/4 inch

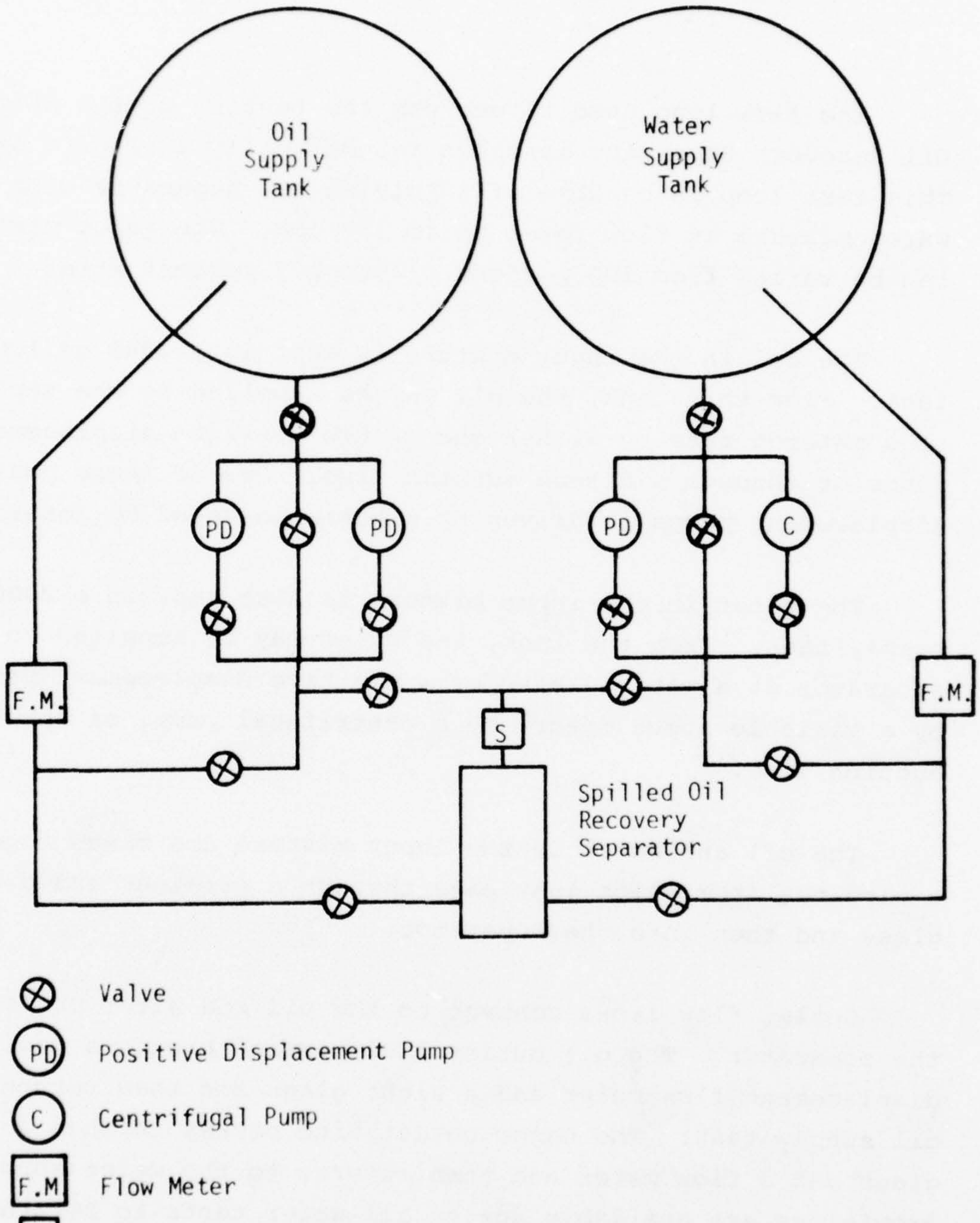


Figure 3-1. Schematic Flow Diagram of Spilled Oil Recovery Separator Test Loop

tubing, perforated along the upstream side, inserted diametrically across the pipe flow. (This design is similar to that used by the CG and USN for oil-water systems testing.) When taking a sample, first the tube is flushed, then one liter is drawn for analysis. Analysis of "free" oil-water mixtures was by using a graduated cylinder with settling times of about one day. (For very low concentrations of oil emulsified in water, we use standard solvent extraction techniques, but this data is not germane to the present effort because the emulsified oil is typically 1000 ppm or less.)

In addition to these connections, the test loop contains separator bypass lines on the oil and water sides.

In addition to the flow meters on the discharge lines, pressure gauges were installed at all important points in the test loop. Pressure gauges were also installed to measure the separator inlet pressure, oil and water outlet pressures, the water control pressure, and the three oil control pressures. An amprobe was available to measure the current being used by the motor driving the separator.

While running tests with high concentration of oil and high flow rate we found that large amounts of oil accumulated in the water tank. Also, with low oil concentration and poor control operation, water accumulated in the oil tank. This was a severe inconvenience, because often the cross-mixing of the oil and water would alter the input concentration so rapidly that stable, optimum control of the separator discharges could never be obtained. This of course required separator shutdown and then trimming of the input tanks before attempting another test.

Prior to the expanded preliminary testing, an oil supply quality maintenance system was installed. This system is shown schematically in Figure 3-2 and was designed to minimize the amount of free water which accumulated in the oil supply.

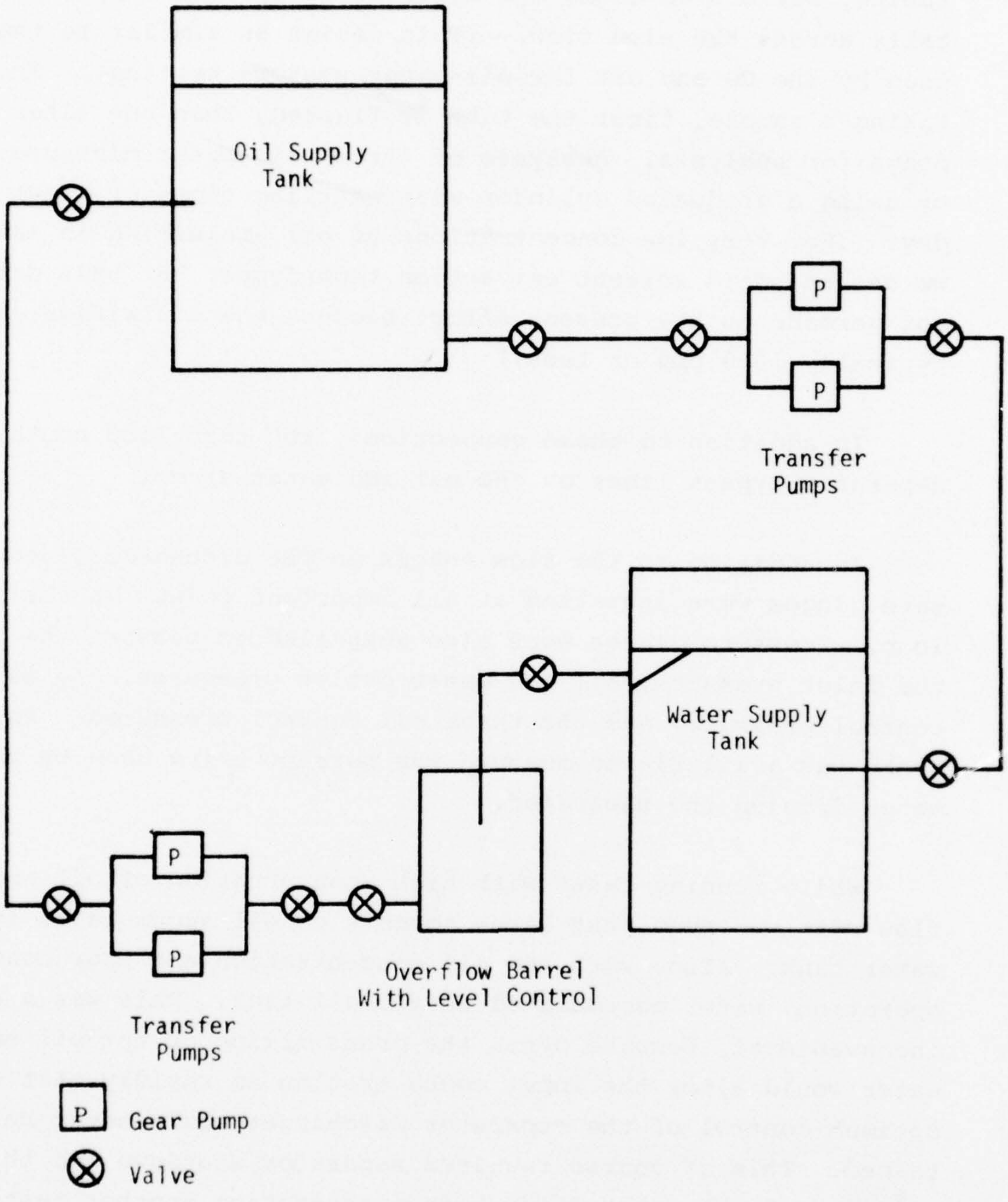


Figure 3-2. Schematic Diagram of Oil Supply Quality Maintenance System

The oil supply quality maintenance system works as follows. While testing is going on, a gear pump continuously pumps liquid from the bottom of the oil supply tank and discharges it just below the surface of the water supply tank. This liquid being pumped is primarily water but contains oil at times. The oil in this liquid rises to the surface of the water supply tank, and any excess flows over an overflow dam into an overflow barrel. A level control on this overflow barrel pumps any accumulated oil back to the oil supply tank.

4. FLUID MECHANICAL PERFORMANCE

The Spilled Oil Recovery Separator was subjected to a number of different tests designed to determine the fluid mechanical performance of the unit. Some of these tests were performed during the preliminary testing of the unit, and some were performed later during an expanded preliminary test series. The results of all this fluid mechanical performance testing are combined and presented in this section.

The fluid mechanical performance testing was designed to determine and quantify five different aspects of the performance of the Spilled Oil Recovery Separator. These five aspects are:

a. Pumping Performance

b. Suction Performance

c. Horesepower Requirements

d. Control Pressure Behavior

e. Air Ingestion Capability

Tests to determine these aspects were performed in the Separator Test Facility described in Section 3. The fluid processed in these tests was water only. Section 4.1 describes the tests that were performed, and Sections 4.2 through 4.6 present the data obtained from these tests.

4.1 Description of the Fluid Mechanical Tests Performed

Four different fluid mechanical performance tests were performed. These tests are described below.

4.1.1 Test No. 1

The purpose of this test was to determine the output and control pressures of the Spilled Oil Recovery Separator over the entire range of possible flow rates.

The tests were performed with water only, at 3600 rpm, and at zero psig inlet pressure. Three different runs were made.

a. With the oil outlet closed, the water outlet flow rate was varied

b. With the water outlet closed, the oil outlet flow rate was varied

c. While maintaining a constant total flow rate, the distribution of this flow between the oil and water outlets was varied.

For each of these runs the water and oil outlet pressures, the water and oil control pressures, and the motor amperage were measured.

4.1.2 Test No. 2

The purpose of this test was to determine the output and control pressures of the Spilled Oil Recovery Separator over the range of possible inlet pressures.

The tests were conducted on water, at 3600 rpm, and at a flow rate of 100 gpm. Two different runs were made:

a. With the oil outlet closed, the inlet pressure was varied while maintaining 100 gpm of flow out the water outlet, and

b. With the water outlet closed, the inlet pressure was varied while maintaining 100 gpm of flow out the oil outlet.

For each of these runs, the water and oil outlet pressures, the water and oil control pressures, and the motor amperage were measured.

4.1.3 Test No. 3

The purpose of this test was to determine the output flow rate capabilities of the Spilled Oil Recovery Separator over the range of possible inlet pressures.

The tests were performed on water. Four runs were made:

a. At 3600 rpm with the oil outlet closed and the water outlet discharge restriction held constant, the inlet pressure was varied

b. At 3600 rpm with the water outlet closed and the oil outlet discharge restriction held constant, the inlet pressure was varied

c. At 3600 rpm with both the oil and water outlet discharge restrictions held constant, the inlet pressure was varied

d. At 2400 rpm with both the oil and water outlet discharge restrictions held constant, the inlet pressure was varied.

For each of these runs, the water and oil outlet pressures, the water and oil control pressures, and the motor amperage were measured.

4.1.4 Test No. 4

The purpose of this test was to determine the effect of ingested air on the Spilled Oil Recovery Separator. This test was conducted qualitatively. A bleed valve was hooked into the separator inlet pipe. With the separator inlet pressure slightly below atmospheric pressure, opening this valve admitted air into the liquid entering the separator and the effects of this air on the separator were noted.

4.2 Pumping Performance - Results from Test No. 1

The pumping performance of the Spilled Oil Recovery Separator is presented in Figures 4-1 through 4-3. These figures present water and oil outlet pressures as a function of flow rate for a rotational speed of 3600 rpm and a zero psig inlet pressure.

Figure 4-1 plots water and oil outlet pressures versus flow rate out the water outlet, with no flow out the oil outlet. Figure 4-2 plots water and oil outlet pressures versus flow rate out the oil outlet with no flow out the water outlet. Figure 4-3 plots water and oil outlet pressures versus flow rate out the water outlet with 100 gpm of total flow through the separator.

4.3 Suction Performance - Results from Tests No. 2 and No. 3

The suction performance of the Spilled Oil Recovery Separator is presented in two different ways in Figures 4-4 through 4-9. Figures 4-4 and 4-5 present water and oil outlet pressures as a function of inlet pressure for a rotational speed of 3600 rpm and a constant flow rate. Figures 4-6 through 4-9 present water and oil outlet flow rates as a function of inlet pressure for constant discharge restrictions.

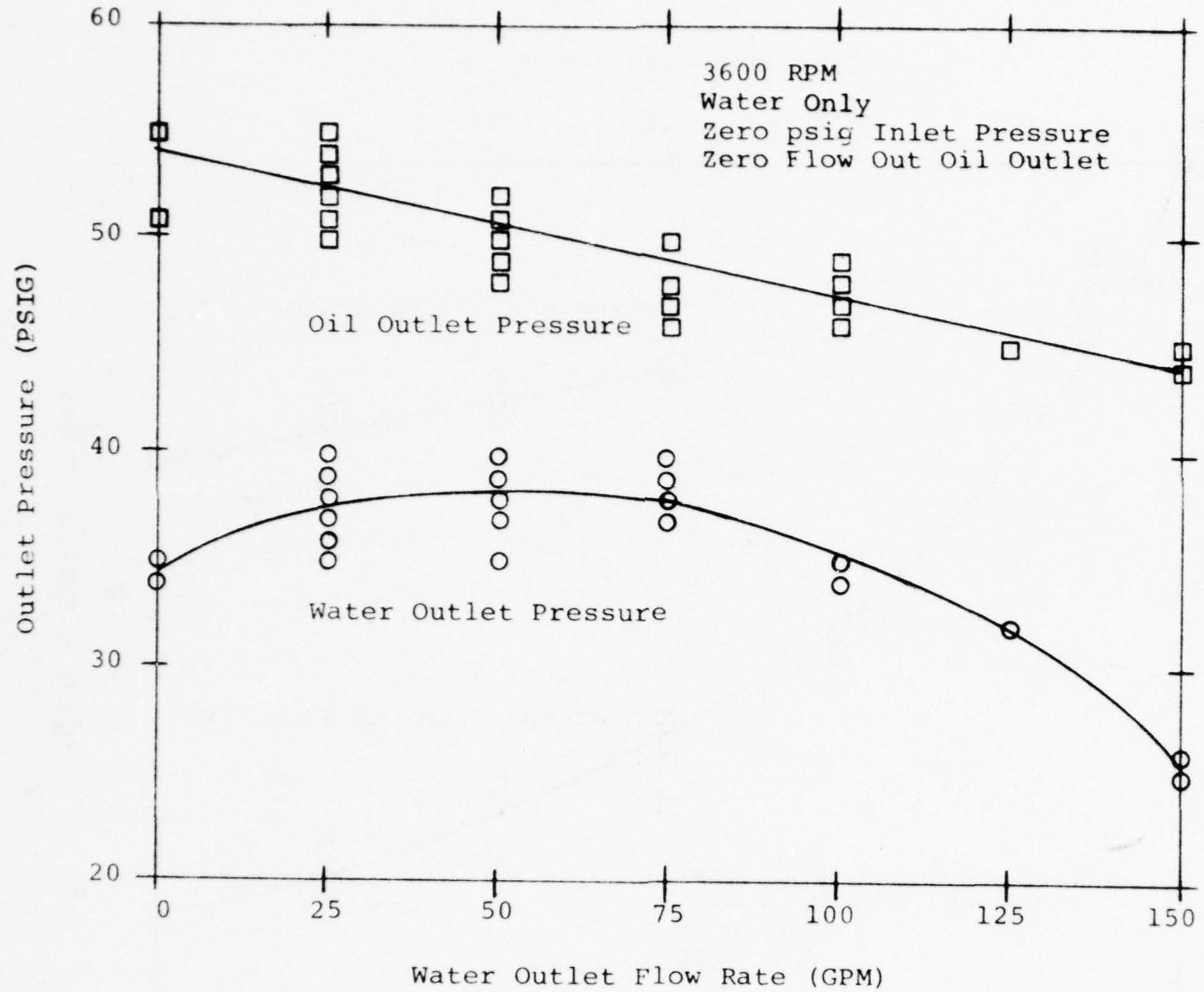


Figure 4-1. Pumping Performance: Outlet Pressures Versus Water Outlet Flow Rate

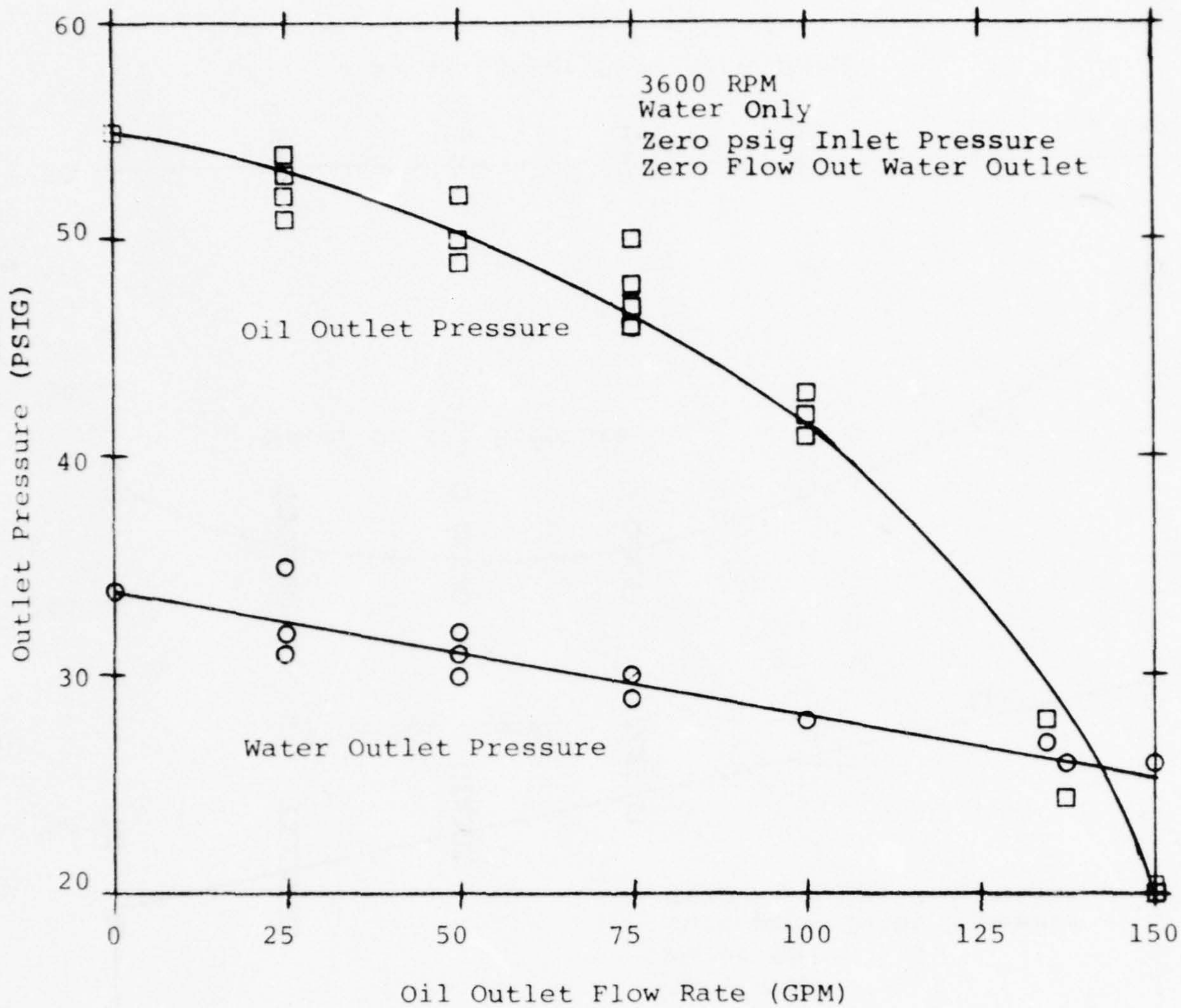


Figure 4-2. Pumping Performance: Outlet Pressures Versus Oil Outlet Flow Rate

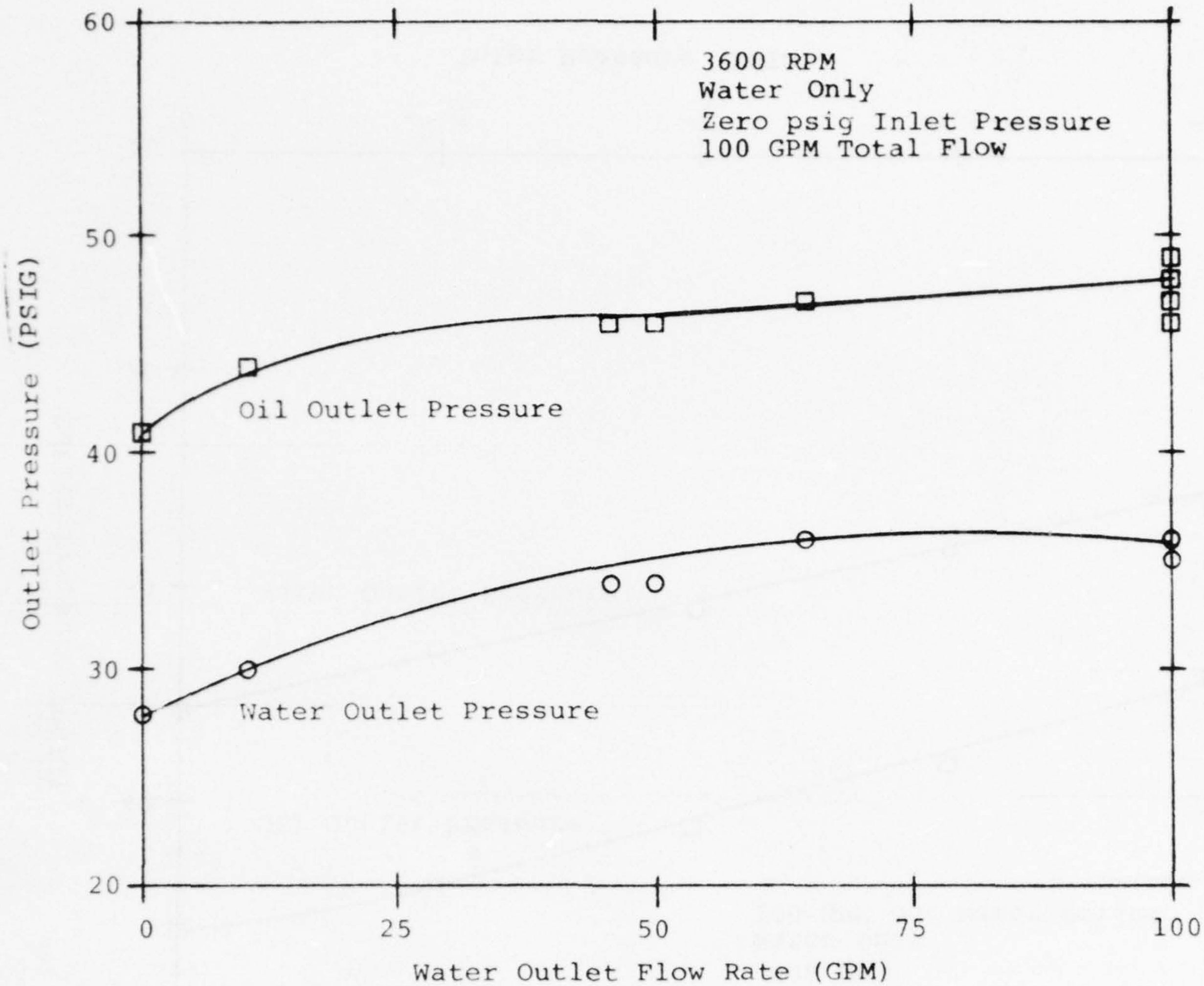


Figure 4-3. Pumping Performance: Outlet Pressures Versus Flow Distribution

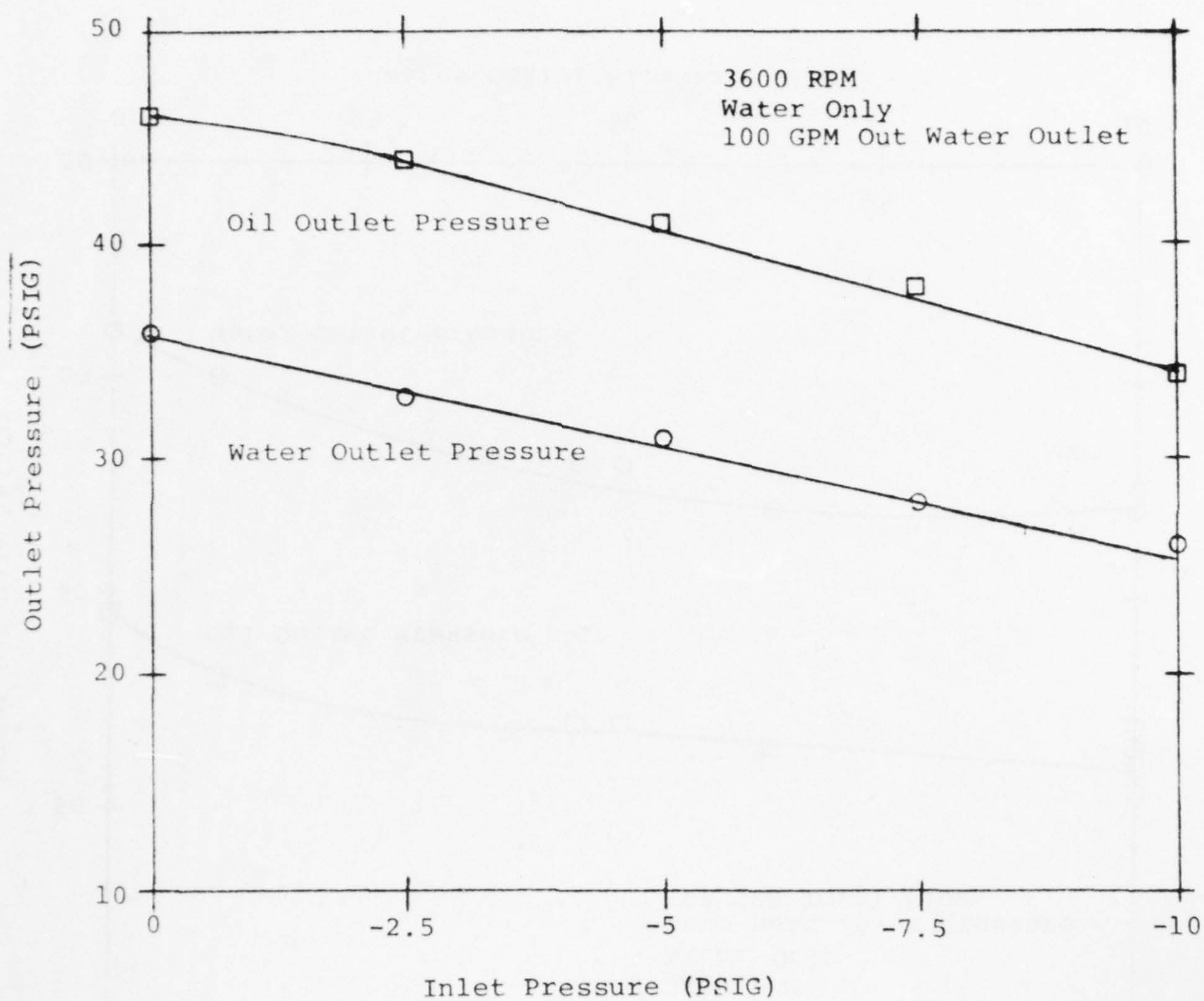


Figure 4-4. Suction Performance: Outlet Pressures Versus Inlet Pressure

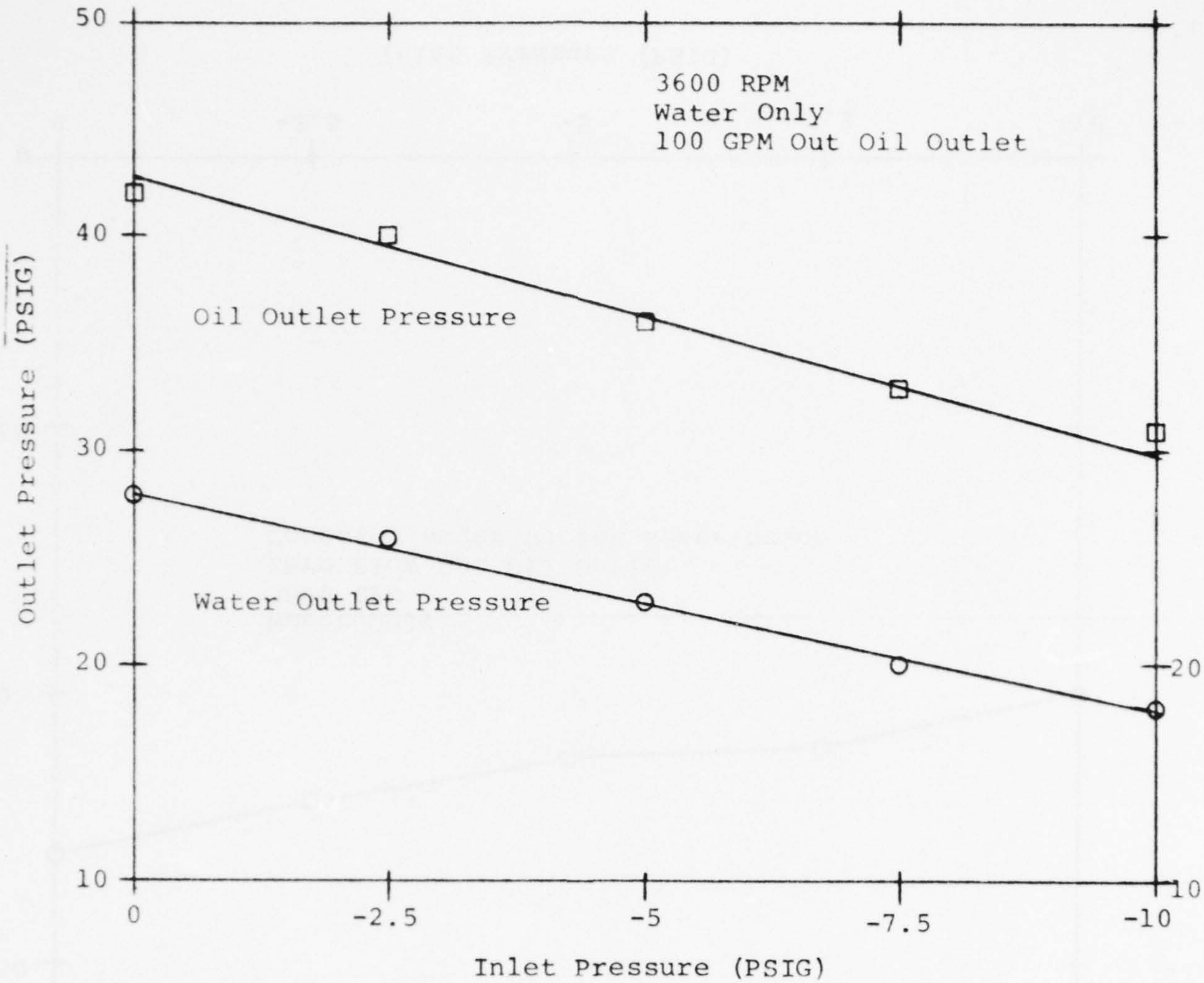


Figure 4-5. Suction Performance: Outlet Pressures Versus Inlet Pressure

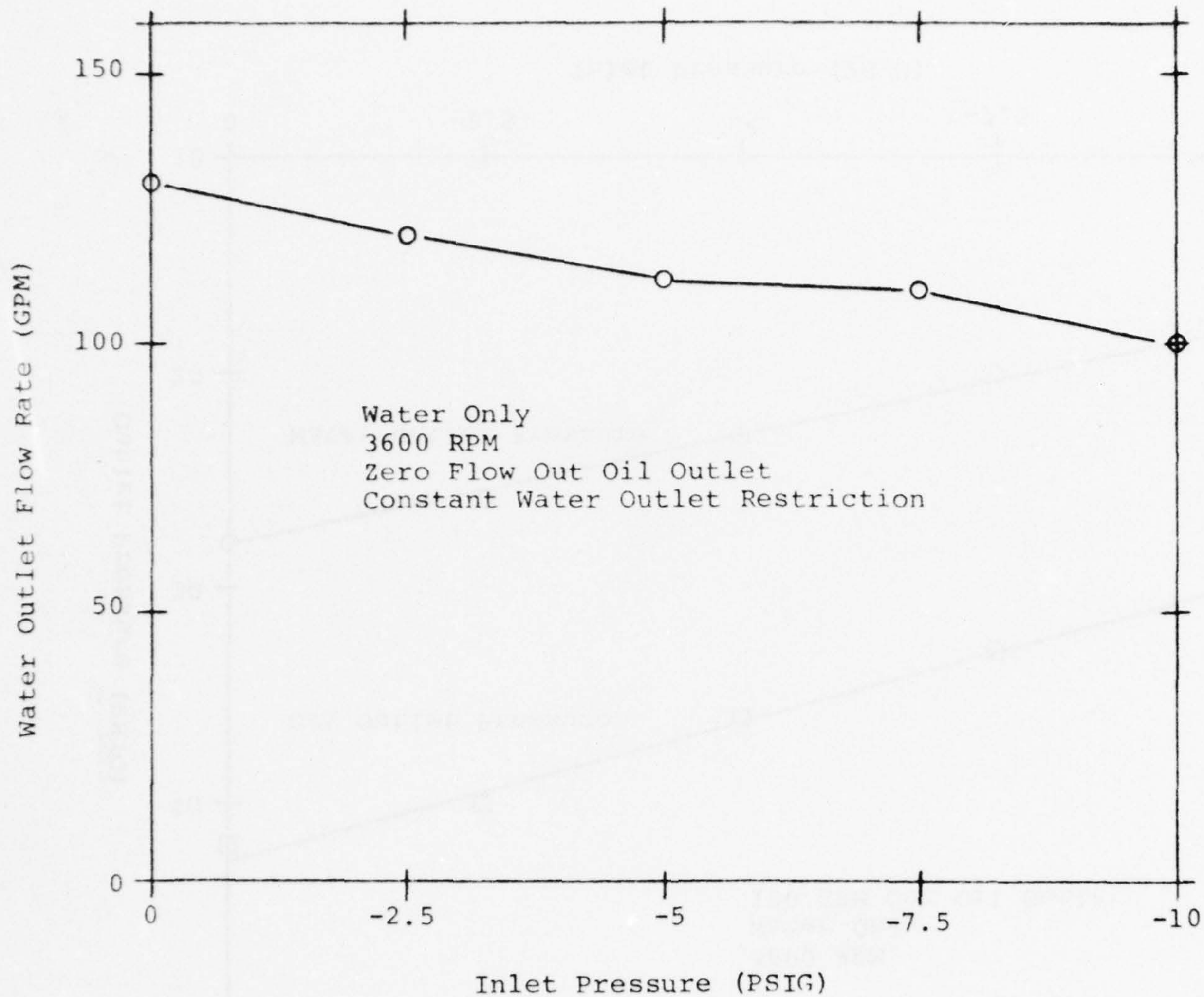


Figure 4-6. Suction Performance: Water Outlet Flow Rate Versus Inlet Pressure

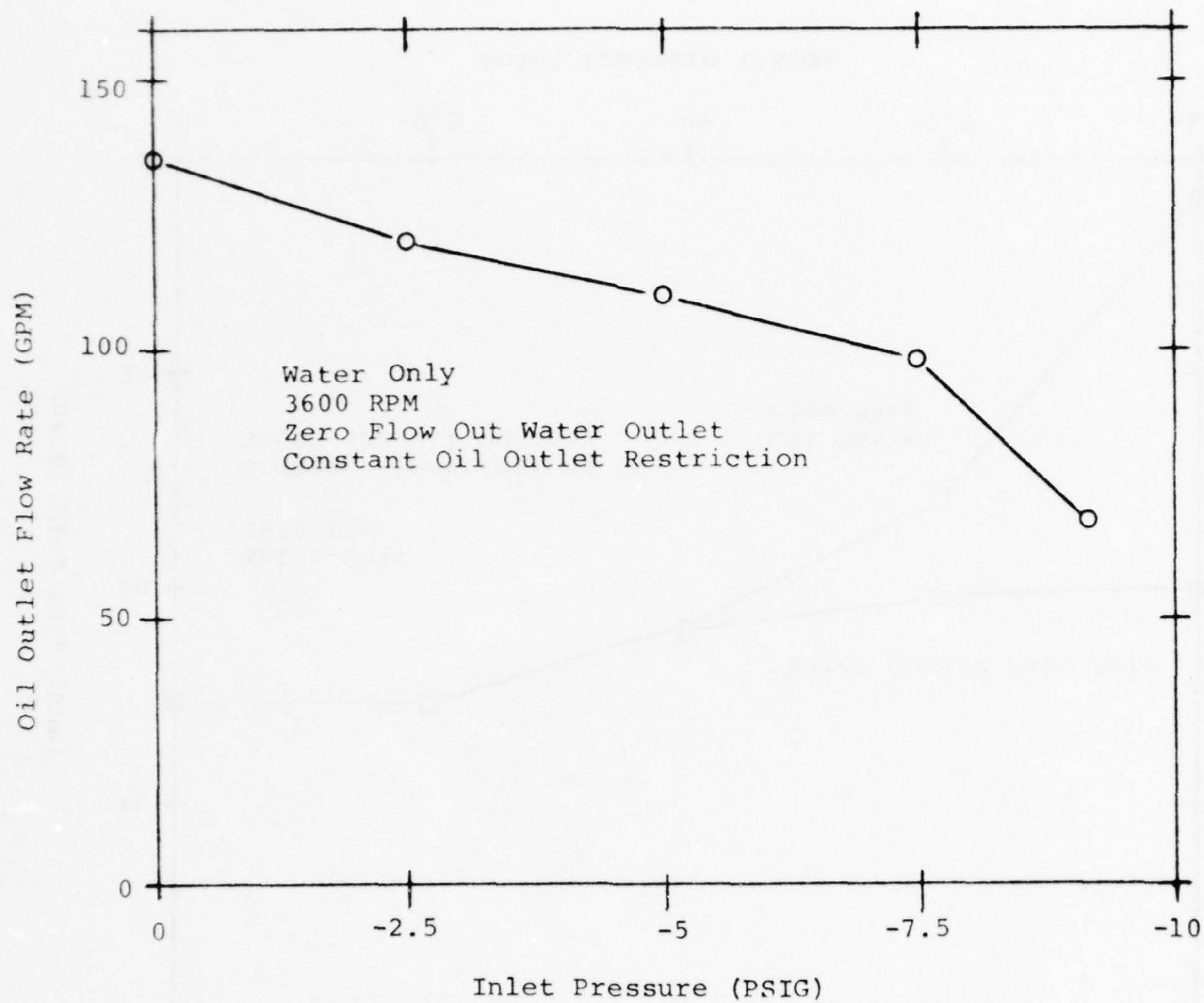


Figure 4-7. Suction Performance: Oil Outlet Flow Rate Versus Inlet Pressure

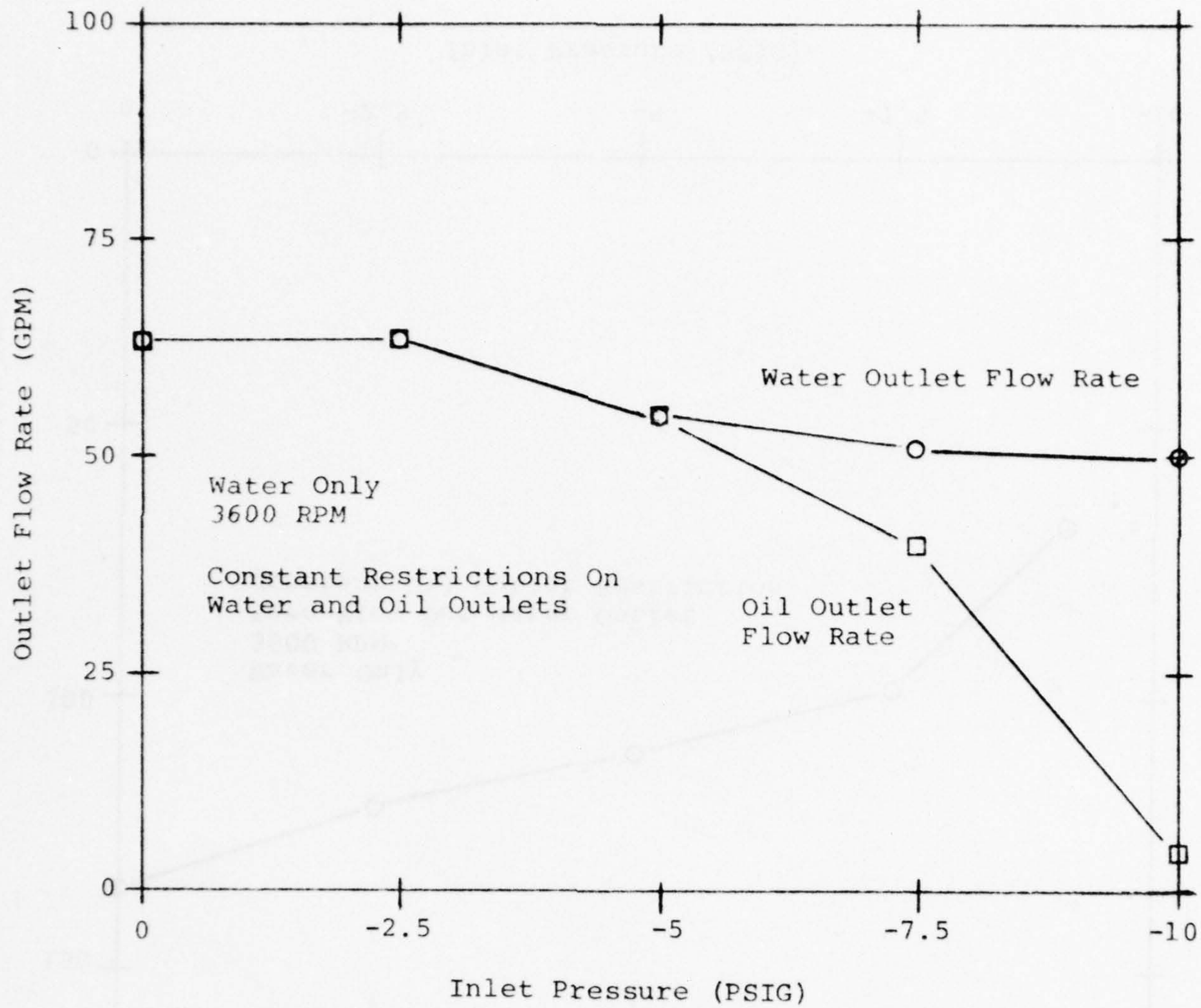


Figure 4-8. Suction Performance: Outlet Flow Rate Versus Inlet Pressure

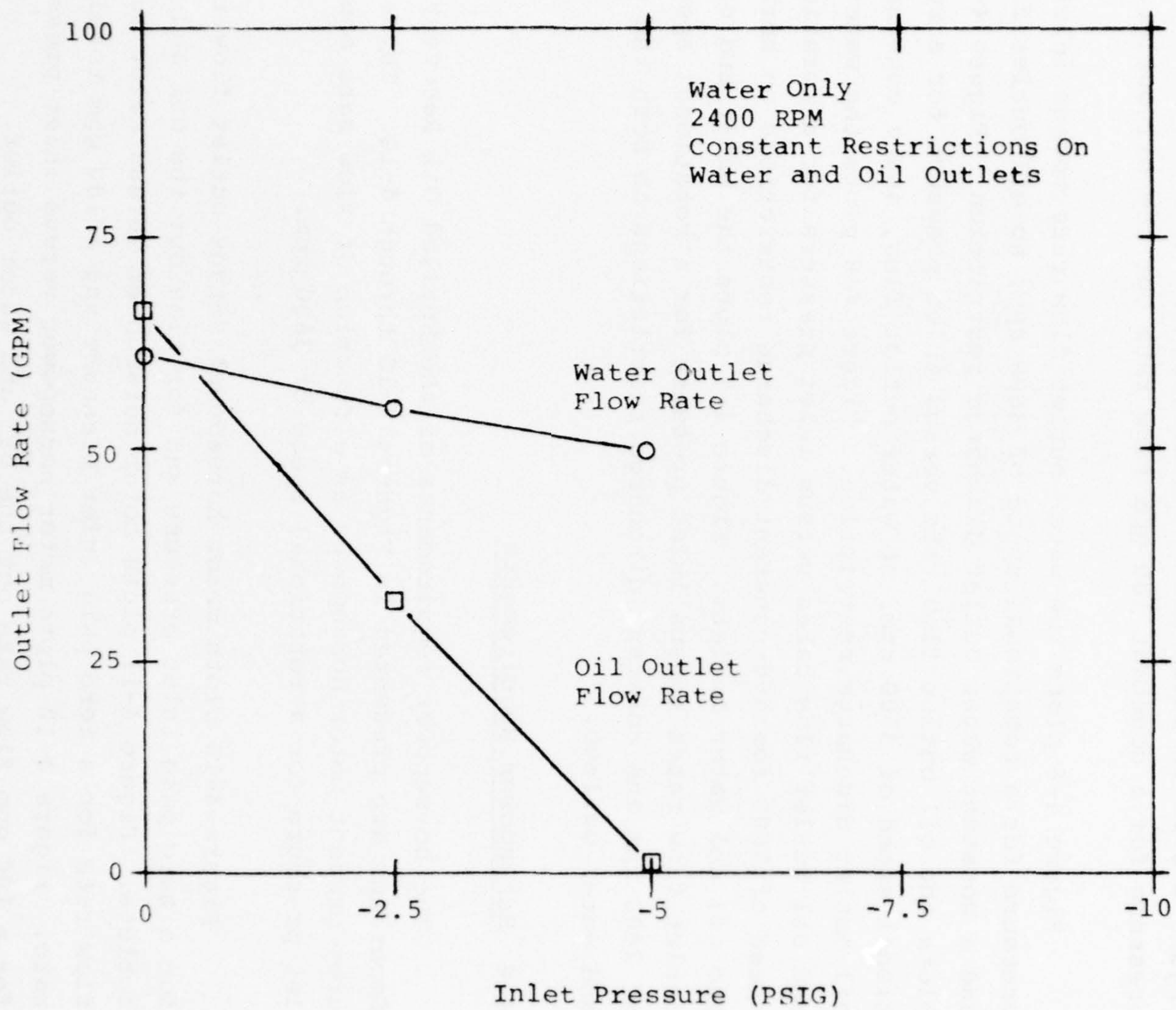


Figure 4-9. Suction Performance: Outlet Flow Rates
Versus Inlet Pressure

Figure 4-4 plots water and oil outlet pressures versus inlet pressure for a constant 100 gpm flow rate out the water outlet. Figure 4-5 plots water and oil outlet pressures versus inlet pressure for a constant 100 gpm flow rate out the oil outlet.

Figure 4-6 plots the water outlet flow rate versus inlet pressure for a rotational speed of 3600 rpm, no oil outlet flow, and a constant water outlet discharge restriction. Figure 4-7 plots the oil outlet flow rate versus inlet pressure for a rotational speed of 3600 rpm, no water outlet flow, and a constant oil outlet discharge restriction. Figure 4-8 plots the water and oil outlet flow rates versus inlet pressure for a rotational speed of 3600 rpm and constant discharge restrictions on both the oil and water outlets. Figure 4-9 plots the water and oil outlet flow rates versus inlet pressure for a rotational speed of 2400 rpm and constant discharge restrictions on both the oil and water outlets.

4.4 Horsepower Requirements

The horsepower requirements of the Spilled Oil Recovery Separator are presented in Figures 4-10 through 4-12. These figures present motor horsepower as a function of flow rate and inlet pressure for a rotational speed of 3600 rpm.

Figure 4-10 plots motor horsepower versus outlet flow rate for a zero psig inlet pressure and for flow out the oil and water outlets. Figure 4-11 plots motor horsepower versus water outlet flow rate for a zero psig inlet pressure and a 100 gpm total flow rate. Figure 4-12 plots motor horsepower versus inlet pressure for a 100 gpm flow rate out the oil and water outlet.

4.5 Control Pressure Behavior - Results from Tests No. 1 and No. 2

The behavior of the oil and water control pressures is described in the following paragraphs.

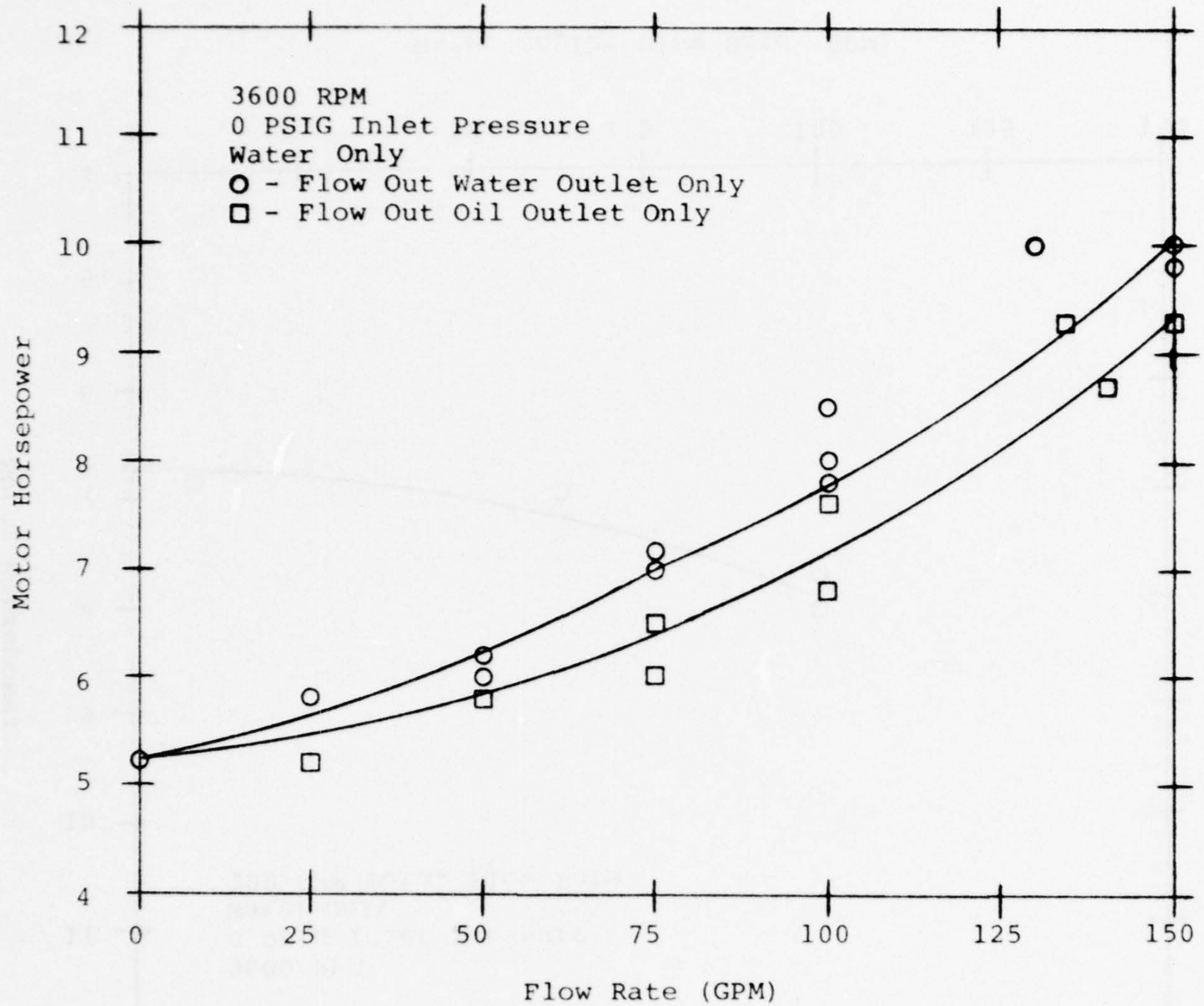


Figure 4-10. Horsepower Requirements Versus Flow Rate

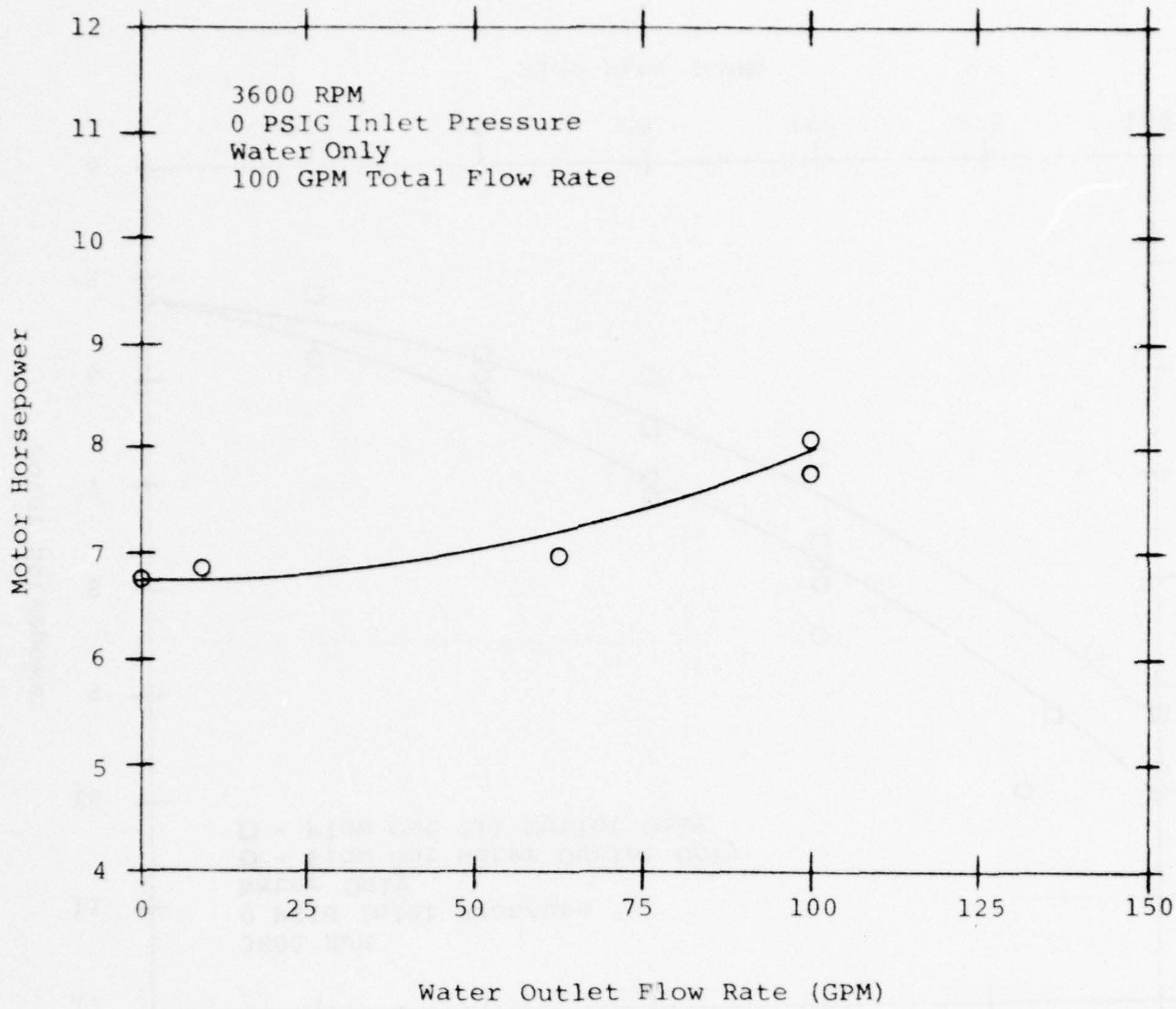


Figure 4-11. Horsepower Requirements Versus Flow Distribution

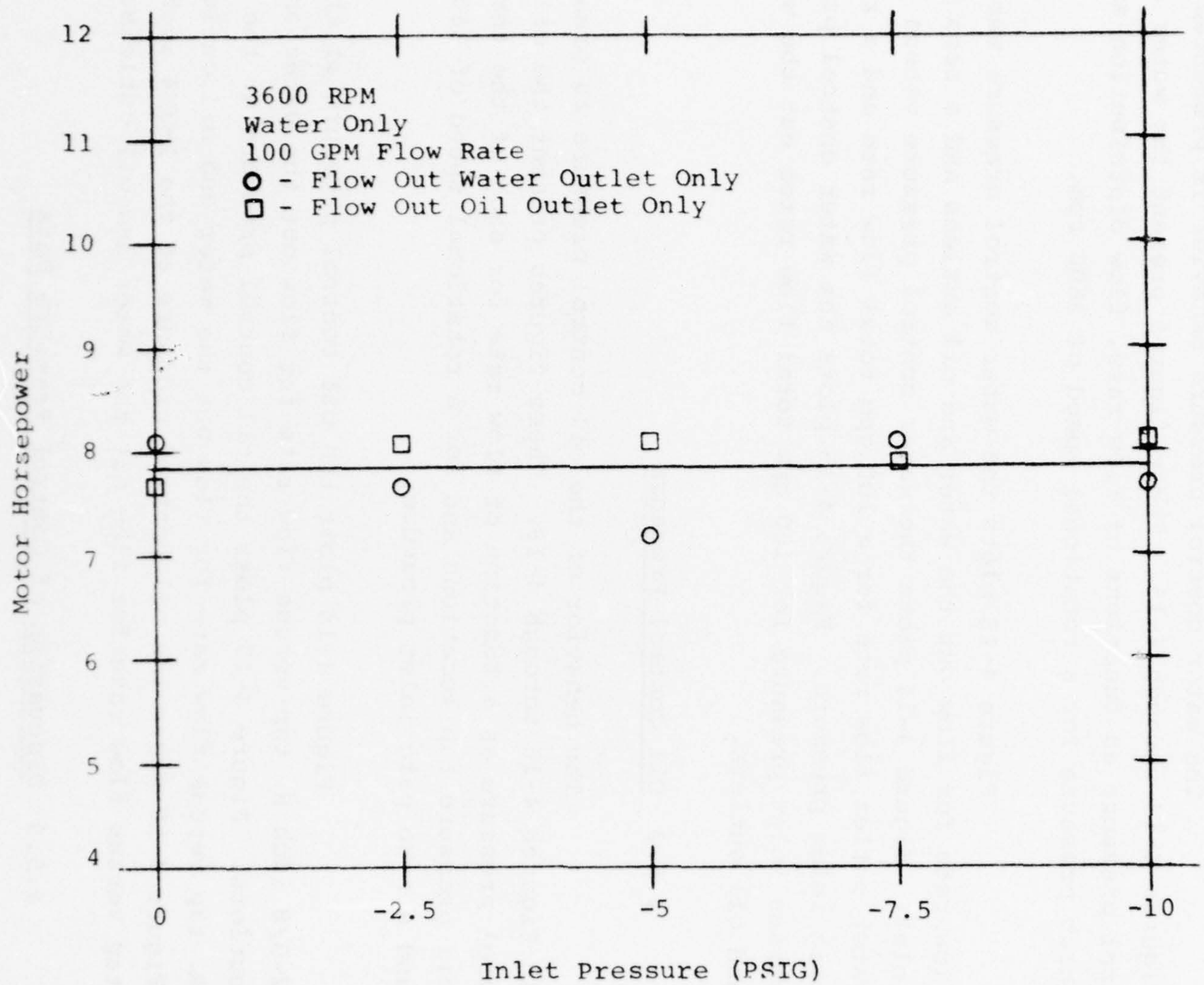


Figure 4-12. Horsepower Requirements Versus Inlet Pressure

4.5.1 Water Control Pressure

The water control pressure behavior is presented in Figures 4-13 through 4-15. These figures present the water control pressure as functions of flow rate, flow distribution and inlet pressure for a rotational speed of 3600 rpm.

Figure 4-13 plots the water control pressure versus flow rate for flow out the water and oil outlets and a zero psig inlet. Figure 4-14 plots the water control pressure versus the water outlet flow rate for a 100 gpm total flow rate and a zero psig inlet pressure. Figure 4-15 plots the water control pressure versus inlet pressure for 100 gpm total flow rates out the water and oil outlets.

4.5.2 Oil Control Pressure

The behavior of the oil control pressure is presented in Figures 4-16 through 4-18. These figures present the oil control pressure as a function of flow rate for each of the three oil pressure tap locations and for a rotational speed of 3600 rpm and a zero psig inlet pressure.

Figure 4-16 plots the oil control pressure at the 2-3/8 inch R. tap versus flow rate for flow out the water and oil outlets. Figure 4-17 plots the oil control pressure at the 2 inch R. tap versus flow rate for flow out the water and oil outlets. Figure 4-18 plots the oil control pressure at the 1-3/4 inch R. tap versus flow rate for flow out the water and oil outlets.

4.5.3 Discussion of Control Pressure Data

Figures 4-13 and 4-14 show that water control pressure decreases with flow rate but is mostly independent of whether this flow discharges through the oil or the water outlet. Figures 4-16 to 4-18 show that the oil control pressures at the

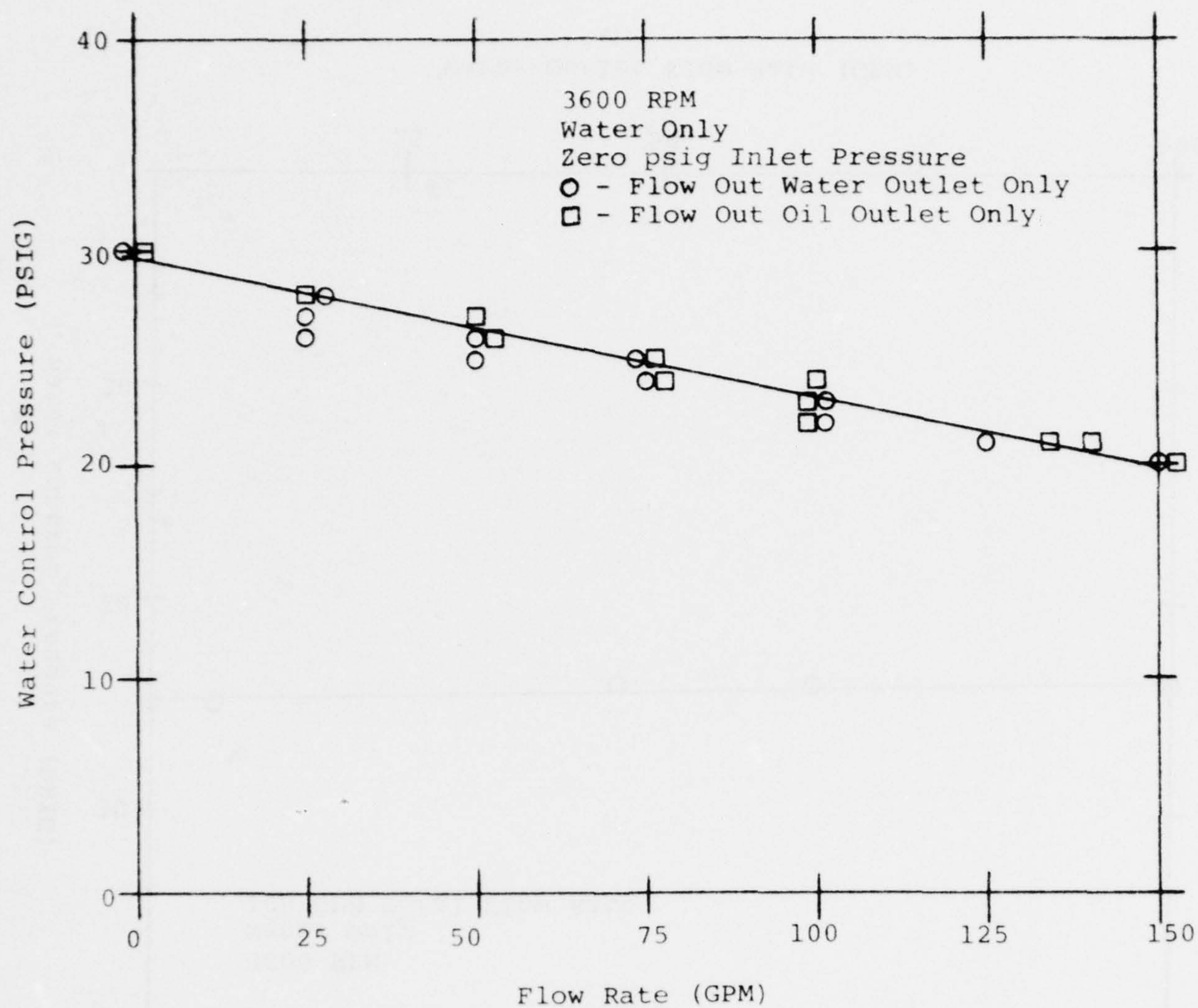


Figure 4-13. Water Control Pressure Versus Flow Rate

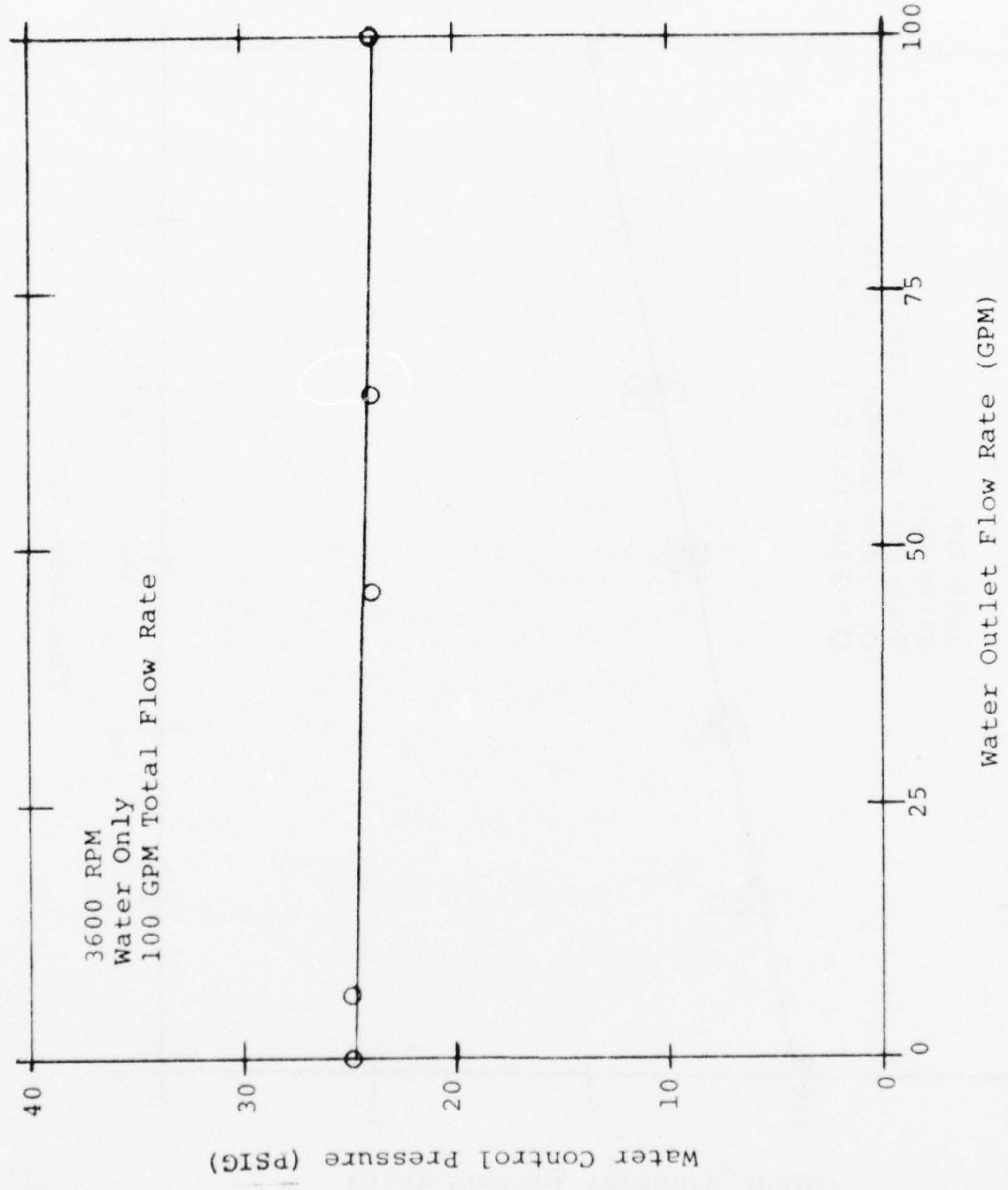


Figure 4-14. Water Control Pressure Versus Flow Distribution

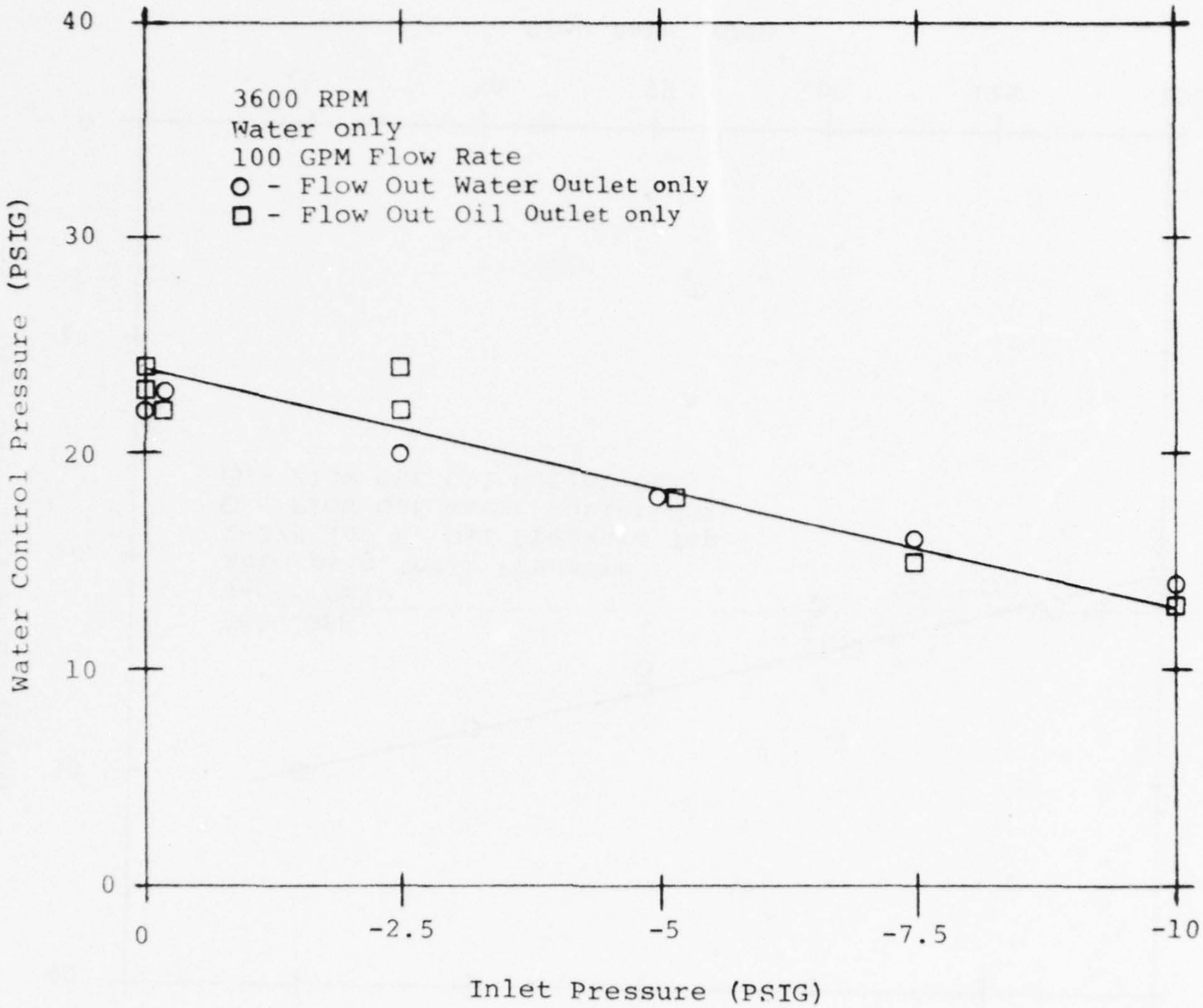


Figure 4-15. Water Control Pressure Versus Inlet Pressure

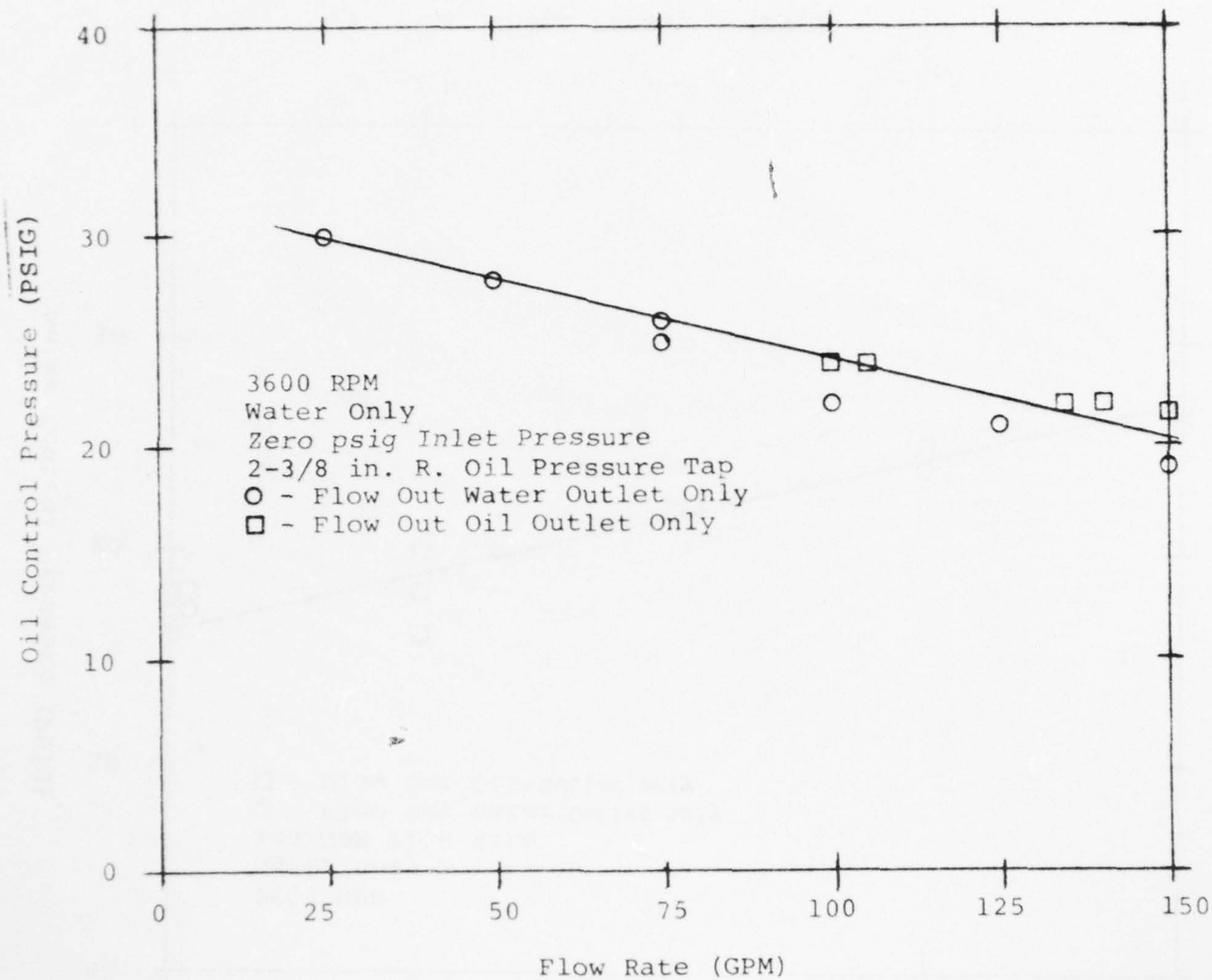


Figure 4-16. Oil Control Pressure Versus Flow Rate for 2-3/8 Inch R. Tap

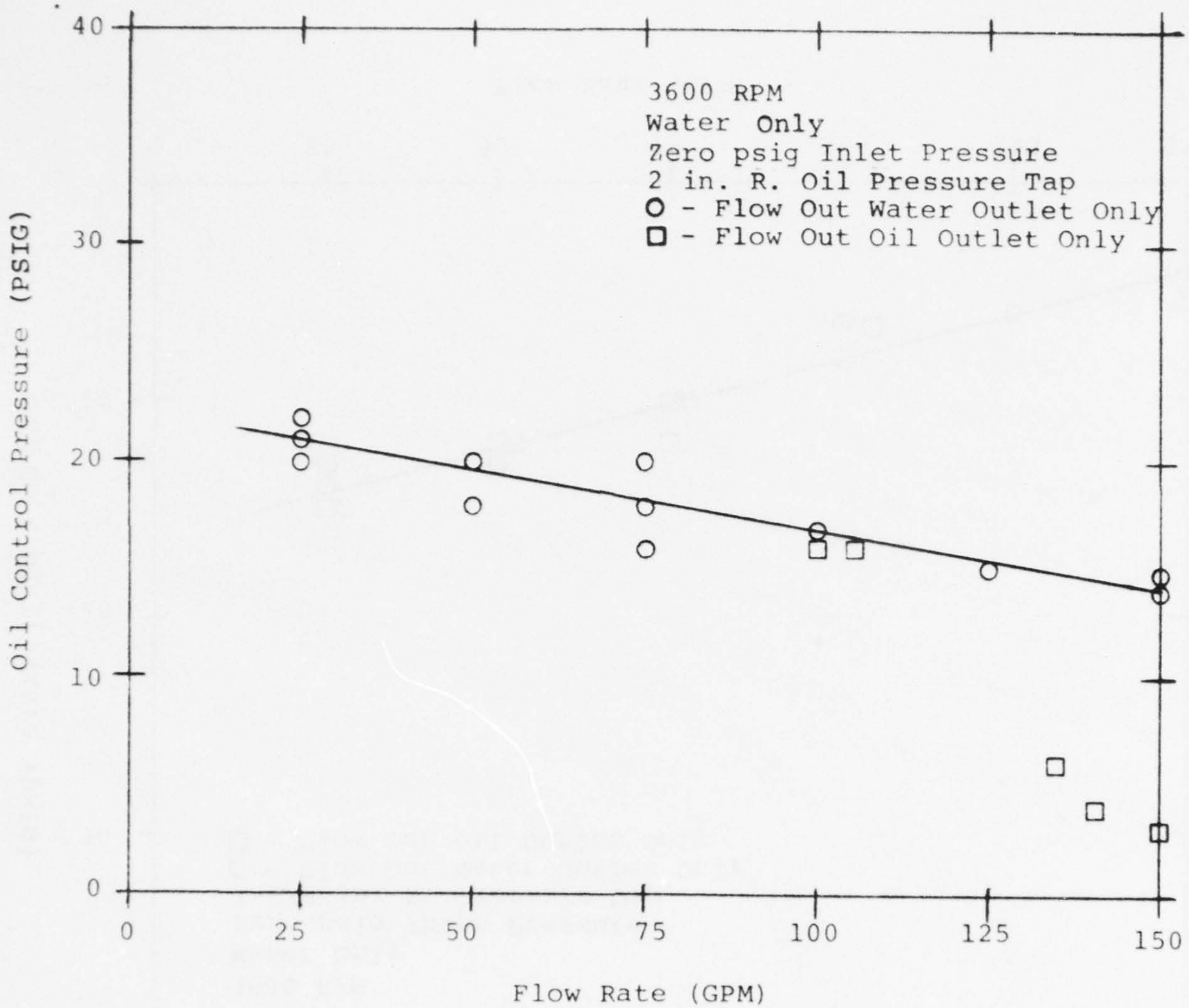


Figure 4-17. Oil Control Pressure Versus Flow Rate for 2 Inch R. Tap

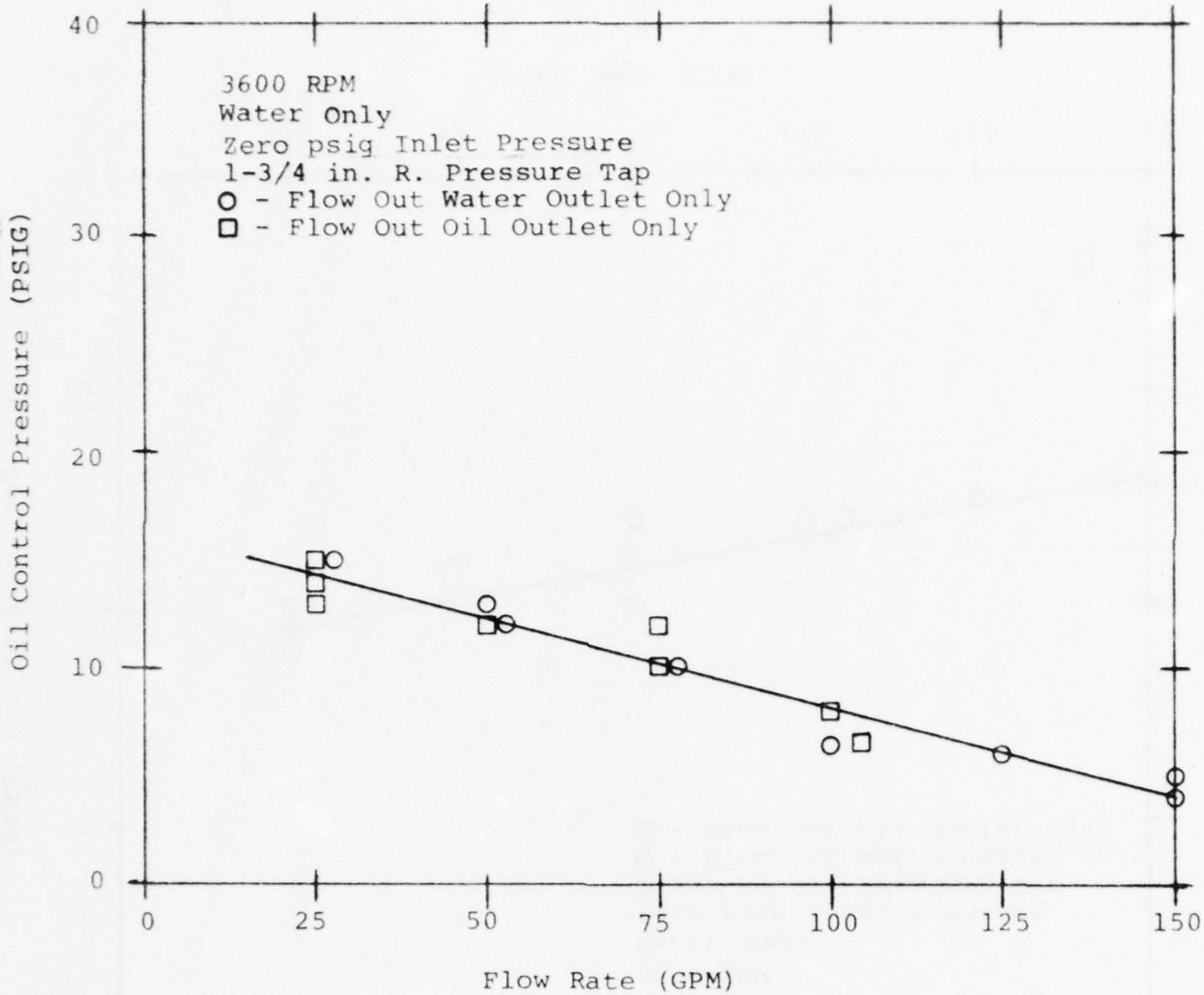


Figure 4-18. Oil Control Pressure Versus Flow Rate for 1-3/4 Inch R. Tap

alternative tap locations also decrease with total flow rate, generally independent of flow outlet location. (The 2-inch tap pressures at very high oil outlet flow are low and anomalous, possibly indicating choked flow in the outlet tube, to be discussed later.) The corresponding decrease of oil and water control pressures independent of outlet location shows that the pressure loss occurs in the inlet section of the rotor, and that this loss does not interfere with the flow control system based on pressure differential between the oil and water outlet taps.

Figure 4-15 also shows that inlet pressure changes need not affect the control system: whether outlet flow is through the water or the oil discharge, the loss in water control pressure is about equal to the loss in inlet pressure. Presumably this affects the oil control pressure in the same way, so that the differential between oil and water pressures does not change due to reduced inlet pressure.

Figure 4-19 shows that the differential control pressure varies very slightly with total flow through the water outlet, in spite of the fact that the absolute values of the control pressures vary significantly. Similarly, Figure 4-20 shows nearly constant control differentials with flow through either oil or water outlets, or both. (Data do not correspond exactly between the two figures because the tests were with different gages and different arrangements of flow-baffles in the rotor.) Note that the data was taken with normal atmospheric inlet pressure.

Figures 4-21 to 4-23 show the effect of reduced inlet pressure on the differential control pressure. If the flow is through the water outlet, the differential remains roughly constant until quite low inlet pressure is reached. However, with 50 gpm through the oil outlet, the differential begins to deviate when inlet pressure goes below -2.5 psi. With 100 gpm through the oil outlet, the differential deviates due to even slight inlet suction. This is not desirable -- nor was it expected.

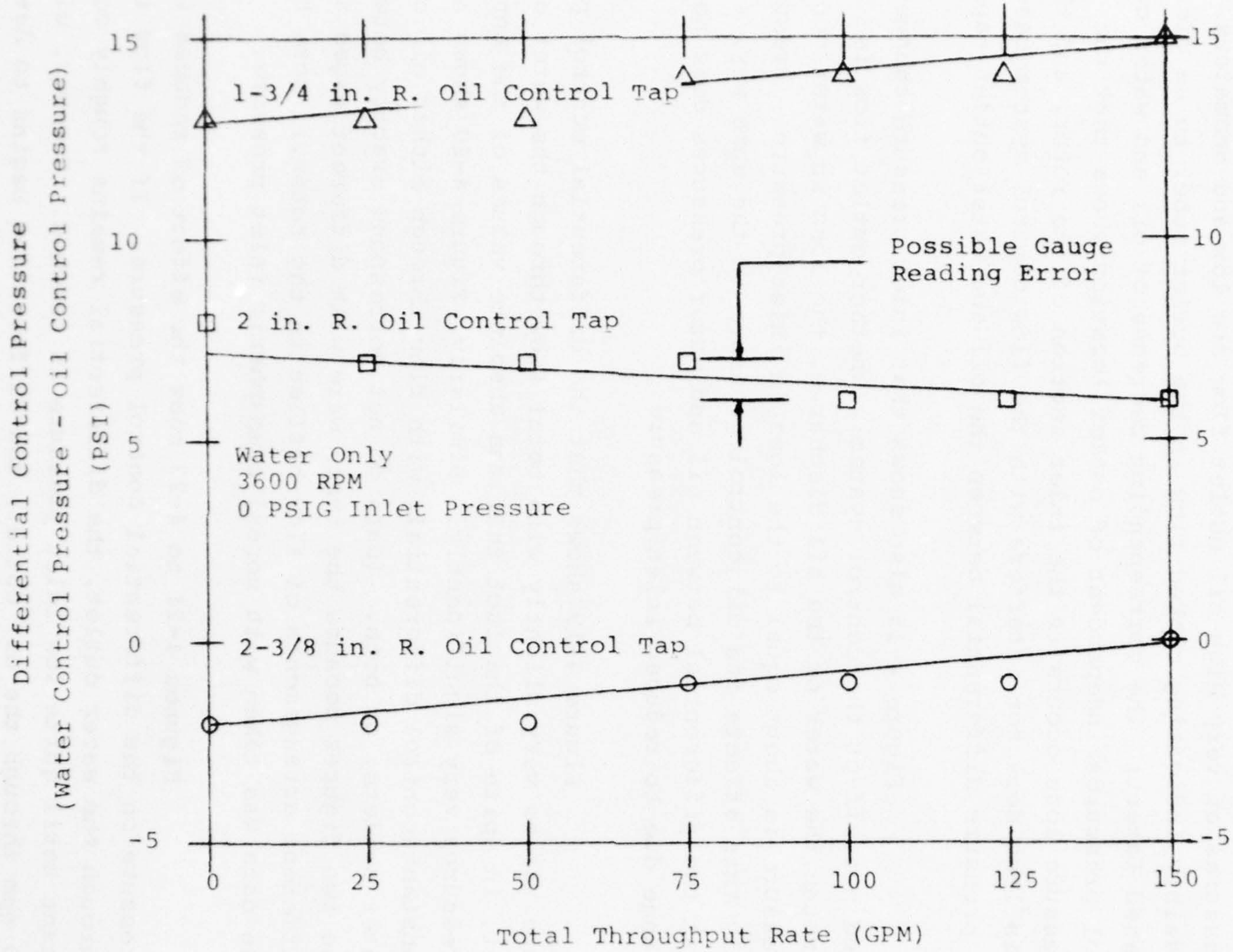


Figure 4-19. Control Differential Pressure Versus Flow Rate

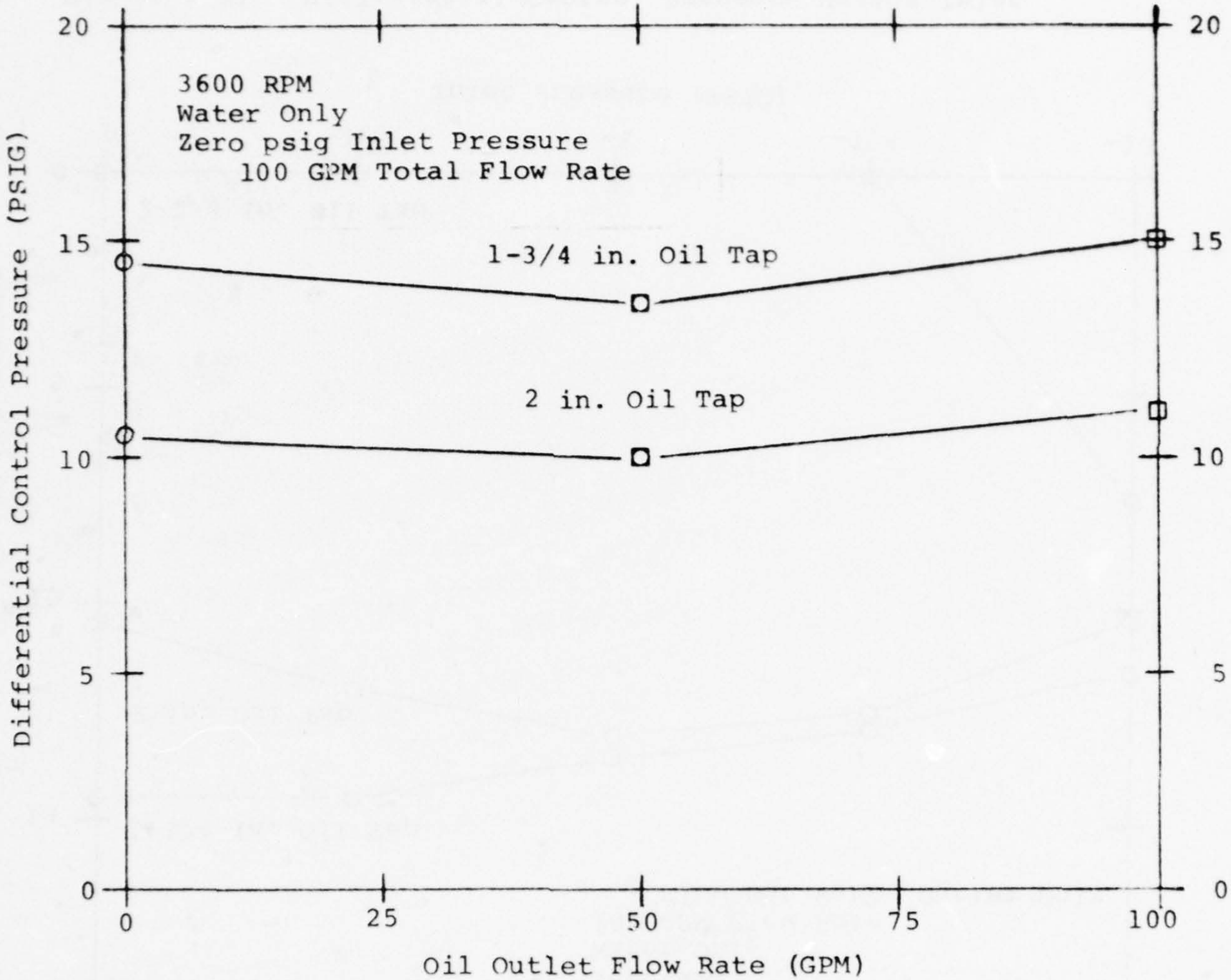


Figure 4-20. Differential Control Pressure Versus Flow Discharge Location

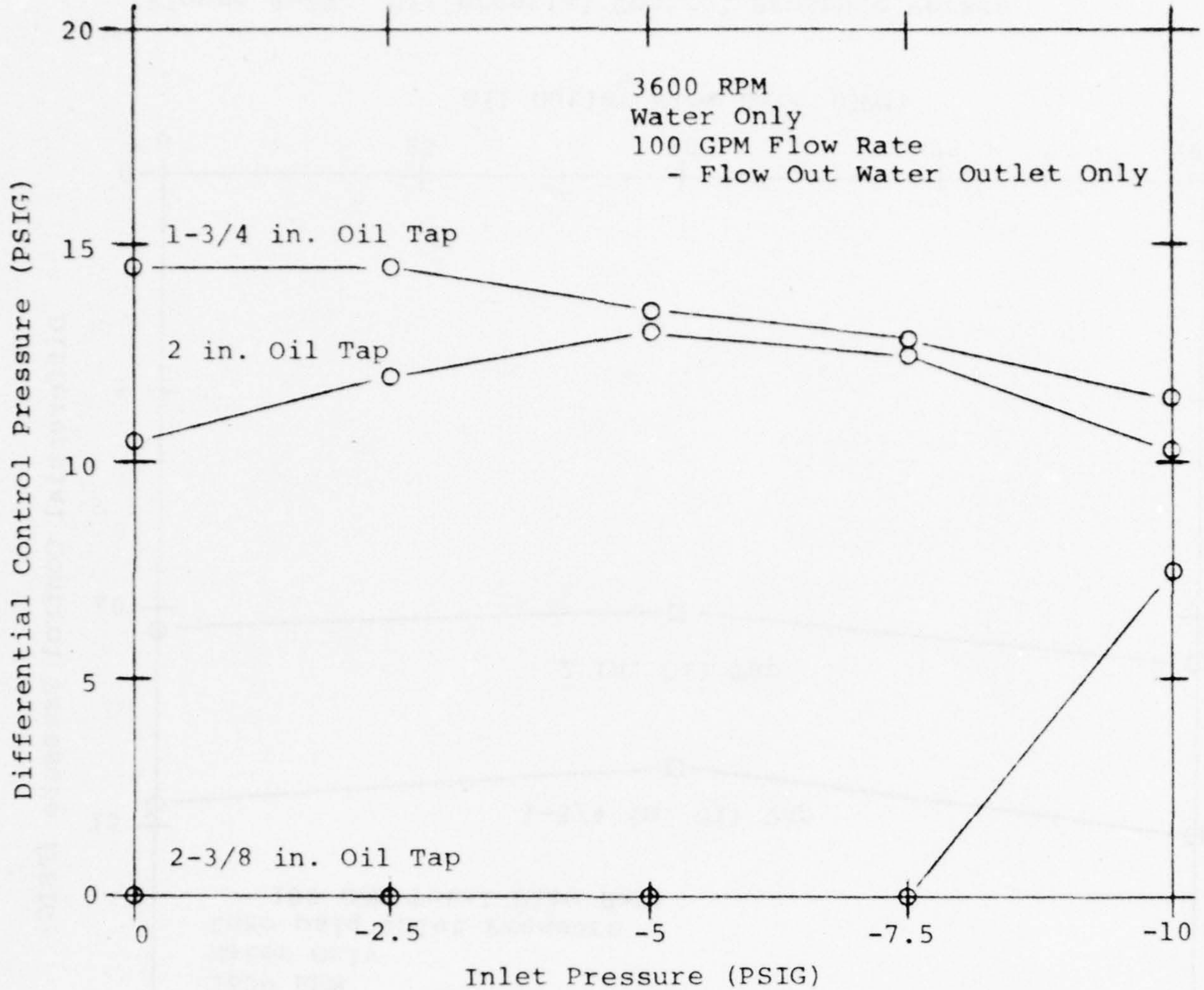


Figure 4-21. Differential Control Pressure Versus Inlet Pressure with Water Outlet Flow

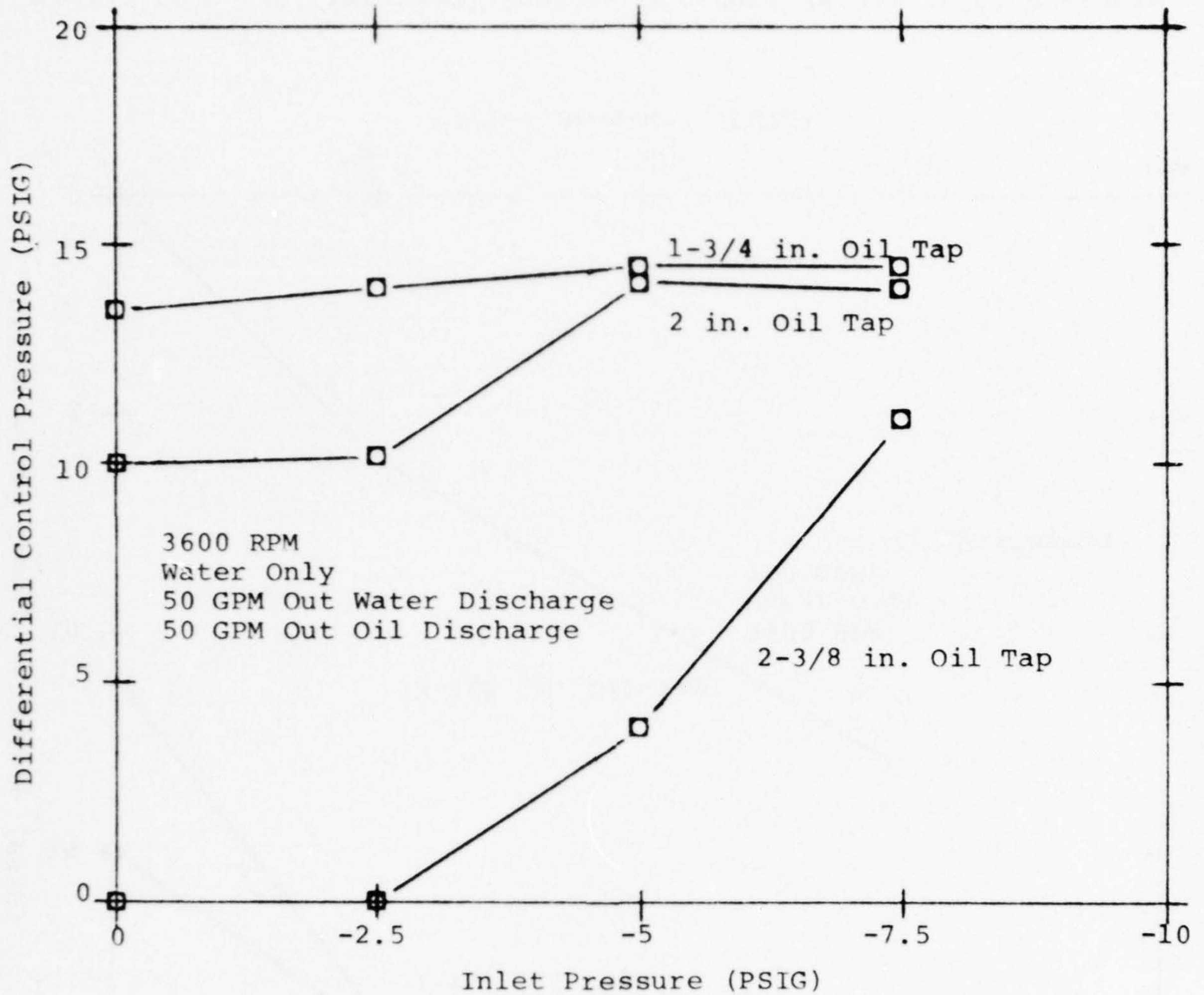


Figure 4-22. Differential Control Pressure Versus Inlet Pressure with Water Flow through Both Oil and Water Outlets

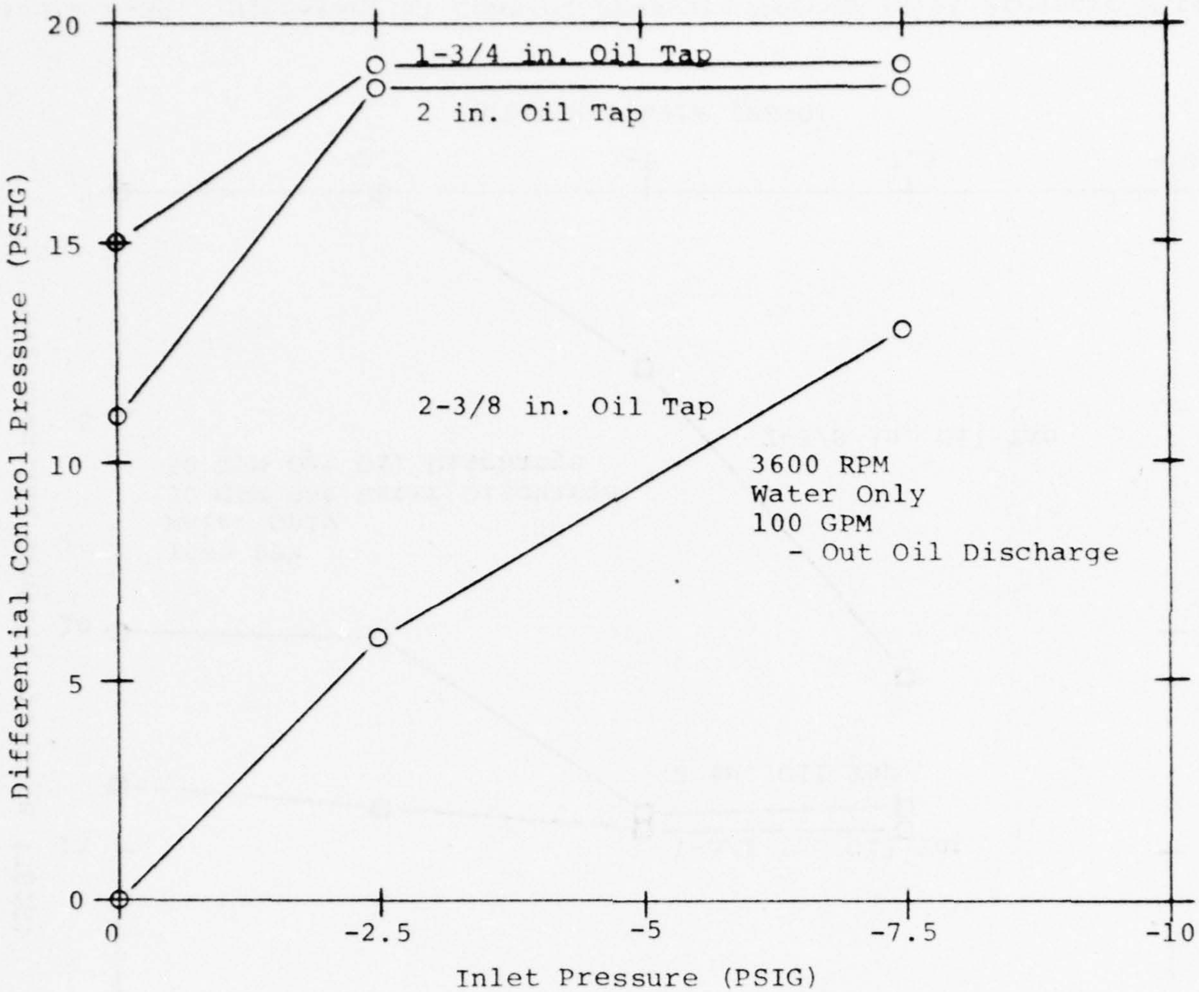


Figure 4-23. Differential Control Pressure Versus Inlet Pressure with Water Flow through Oil Outlet

The reason for the abrupt change in control pressure differential due to a combination of greater inlet suction and flow through the oil outlet is probably due to supercritical, open-channel flow "choking" in the oil discharge tube of the rotor. Initial data discussed in Appendix A led to the conclusion that air was accumulating in the rotor core and an air bleed was provided in the shaft through the centerline. In addition, sheet metal vanes were inserted in the oil outlet tube to reduce vorticity and obscure pressure losses. These were improvements at normal inlet pressure. However, with or without the improvements, the air core in the rotor increases in size with decreasing inlet pressure, by inherent centrifugal action. This reduces the available annulus for flow in the oil outlet tube, and this flow is restricted by shallow channel wave dynamics. (The tube is the "bottom" of the flow channel, and the air core the "surface".) This situation can be alleviated by using a larger diameter, shorter outlet tube and reducing inlet losses to a minimum. Another alternative that is less convenient is to measure the oil control pressure inside the rotor by means of a signal conduit in the oil outlet tube and a sealed connection to the housing.

4.6 Air Ingestion Capability - Results from Test No. 4

The air ingestion capability of the Spilled Oil Recovery Separator was determined in a qualitative manner.

With the separator processing 100 gpm of flow and the inlet pressure slightly below atmospheric, opening the bleed valve on the inlet side of the separator the slightest bit would cause the separator to air lock, resulting in a loss of discharge pressures and flow rates. No attempts were made to quantify the amount of air being ingested, but it was a small percentage of the inlet flow rate, say 10 to 30 percent by volume.

5. AUTOMATIC CONTROL AND SEPARATION PERFORMANCE TESTING

The Spilled Oil Recovery Separator was subjected to a considerable amount of testing on oil/water mixtures. This testing had two distinct purposes:

a. To debug and optimize the operation of the automatic discharge control system

b. To determine the separation performance of the unit.

The testing performed for each of these purposes and the data obtained are presented in the following paragraphs. Conclusions drawn on the basis of this data are presented in Section 6.

5.1 Automatic Discharge Control Testing and Performance

The purpose of the testing performed here was to debug and optimize the performance of the automatic effluent discharge controls. Optimization of the operation of the automatic controls consisted of determining the needle valve openings, pilot valve set points, and manual valve positions which provided the best all around performance.

This testing was primarily qualitative in nature, was performed on No. 2 fuel oil, and very few samples were taken. The automatic effluent discharge controls were tested in two stages.

Because the oil outlet control was similar to that employed on other FMA separators, it was initially installed and tested by itself. Thus, the first portion of these tests were performed with the oil effluent controlled automatically and the water effluent controlled manually. This stage of testing was initially performed using the centrifugal pump to provide the

water supply and the variable speed positive displacement pump to provide the oil supply in the inlet mixture. This combination of supply pumps allowed testing at inlet concentrations up to roughly 50 percent oil. Some typical tests results are presented in Table 5-1.

During this portion of automatic oil effluent controls testing, the separator and controls were operating very satisfactorily. It was possible to tune the oil outlet controls, so that the separator provided oil with no visible water and water with less than a few percent oil. In addition to this, the oil control would completely shut off the oil outlet flow when no oil was being fed to the separator.

To obtain higher inlet concentrations than 50 percent, the centrifugal pump on the water supply side was replaced with the variable speed positive displacement pump. This replacement allowed inlet concentration up to roughly 75 percent oil.

During this portion of the automatic oil effluent controls testing, the performance of the separator and controls was acceptable though not as good as that previously obtained. It was again possible to tune the oil outlet controls so that the oil outlet contained no visible water, the water outlet contained only a few percent oil, and the oil outlet shut off when no oil was being introduced. However, the inlet and outlet pressure variations were greater than they had been when the centrifugal pump had been supplying the water.

At this point, the second stage of the automatic effluent discharge control testing began and the automatic controls were installed on the water discharge. Now both discharge paths from the separator were controlled automatically. This stage of testing was performed using variable speed positive displacement

Table 5-1. Automatic Control Test Results

Total Flow Rate (GPM)	Inlet Oil Concentration percent	Oil in Water Outlet percent	Water in Oil Outlet percent
A. Oil Outlet on Automatic Control, Water Outlet on Manual Control, Centrifugal Pump on Water Supply			
95	5%	2200ppm	26%
100	10%	3600ppm	NVW
105	14%	<1%	NVW
105	19%	6%	NVW
105	19%	6400ppm	NVW
110	27%	5-6%	NVW
110	36%	24%	NVW
B. Oil and Water Outlets on Automatic Control, Positive Displacement Pump on Water Supply			
85	29%	1-2%	NVW
100	50%	1-2%	NVW
100	75%	58%	NVW
100	75%	12%	NVW
100	75%	7%	NVW
100	50%	<1%	10%
100	15%	<1%	2%
100	40%	1-2%	4%
100	55%	1-2%	5%
100	80%	<1%	3%
100	90%	<1%	2%

*NVW stands for no visible water and means that after sitting overnight there was no separate water visible in the sample jar.

pumps to supply both the oil and the water in the inlet mixture. Testing covered the entire range from 100 percent water to 100 percent oil.

During this stage of the automatic controls testing, operation proved to be variable and was characterized by large variations in the inlet and outlet pressures. Some typical results from these tests are presented in Table 5-1.

At several instances during these tests of both the oil and water discharge controls, acceptable performance was obtained. This performance can be characterized as follows:

a. At zero percent inlet oil concentration, the oil outlet flow shut off

b. At 100 percent inlet oil concentration, the water outlet flow shut off.

c. At intermediate inlet oil concentration, the water outlet contained less than 2 percent oil and the oil outlet contained less than 5 percent water.

However, the following day, utilizing the same combination of control settings, which resulted in the above performance, the performance deteriorated badly, and extreme pressure variations were experienced.

5.2 Separation Performance Testing

The purpose of this testing was to determine the separation performance of the Spilled Oil Recovery Separator and the range of control pressure differences which result in acceptable

performance. Four types of tests were performed to determine the effect of:

a. Inlet oil concentration

b. Total throughput rate

c. Rotational speed

d. Oil type

For each of these tests, the separator was supplied with a specific set of inlet conditions - inlet oil concentration, throughput flow rate, and oil type. By appropriate adjustment of the oil and water discharge flow rates, the control differential pressure was varied. All of these tests were performed at a zero psig inlet pressure.

At the various control pressures, water and oil outlet samples were taken. The amount of oil in the water outlet samples was determined either by measurement or by carbon tetrachloride extraction/infrared spectrophotometer analysis as appropriate. The amount of water in the oil outlet sample was measured. Occasionally an oil outlet sample was centrifuged in a small laboratory centrifuge to determine the amount, if any, of water entrained in the oil.

The specific inlet conditions tested are described below and the results obtained are presented below.

5.2.1 Inlet Concentration Tests

The tests to determine the effect of inlet concentration on the separation performance of the Spilled Oil Recovery Separator were run on No. 2 fuel oil and water at a total throughput flow rate of 100 gpm, an inlet pressure of zero psig and a

rotational speed of 3600 rpm. Inlet concentration of 10, 25, 50, 75, and 90 percent were tested. The results of these tests are presented in Figures 5-1 through 5-5.

5.2.2 Total Throughput Rate Tests

The tests to determine the effect of total throughput flow rate on the separation performance of the Spilled Oil Recovery Separator were run on No. 2 fuel oil and water at a rotational speed of 3600 rpm and an inlet pressure of zero psig.

Three tests were run: a total throughput rate of 60 gpm with an inlet concentration of 50 percent; a total throughput rate of 140 gpm with inlet concentrations of 25 and 50 percent. These tests, when combined with the results presented in Figures 5-2 and 5-3, provide a good picture of the effect of total throughput rate on separation performances. The results of these tests are presented in Figures 5-6 and 5-7.

5.2.3 Rotational Speed Tests

The tests to determine the effect of rotational speed on the separation performance of the Spilled Oil Recovery Separator were run on No. 2 fuel oil and water at a total throughput rate of 100 gpm, a rotational speed of 2400 rpm, and an inlet pressure of zero psig. Inlet concentrations of 10 and 90 percent were tested. These results are presented in Figure 5-8 and 5-9 and, when combined with the results presented in Figures 5-1 and 5-5, provide an idea of the effect of rotational speed on separation performance.

5.2.4 Oil Type Tests

The tests to determine the effect of oil type on the separation performance of the Spilled Oil Recovery Separator were run on No. 6 fuel oil and water, at a rotational speed of 3600

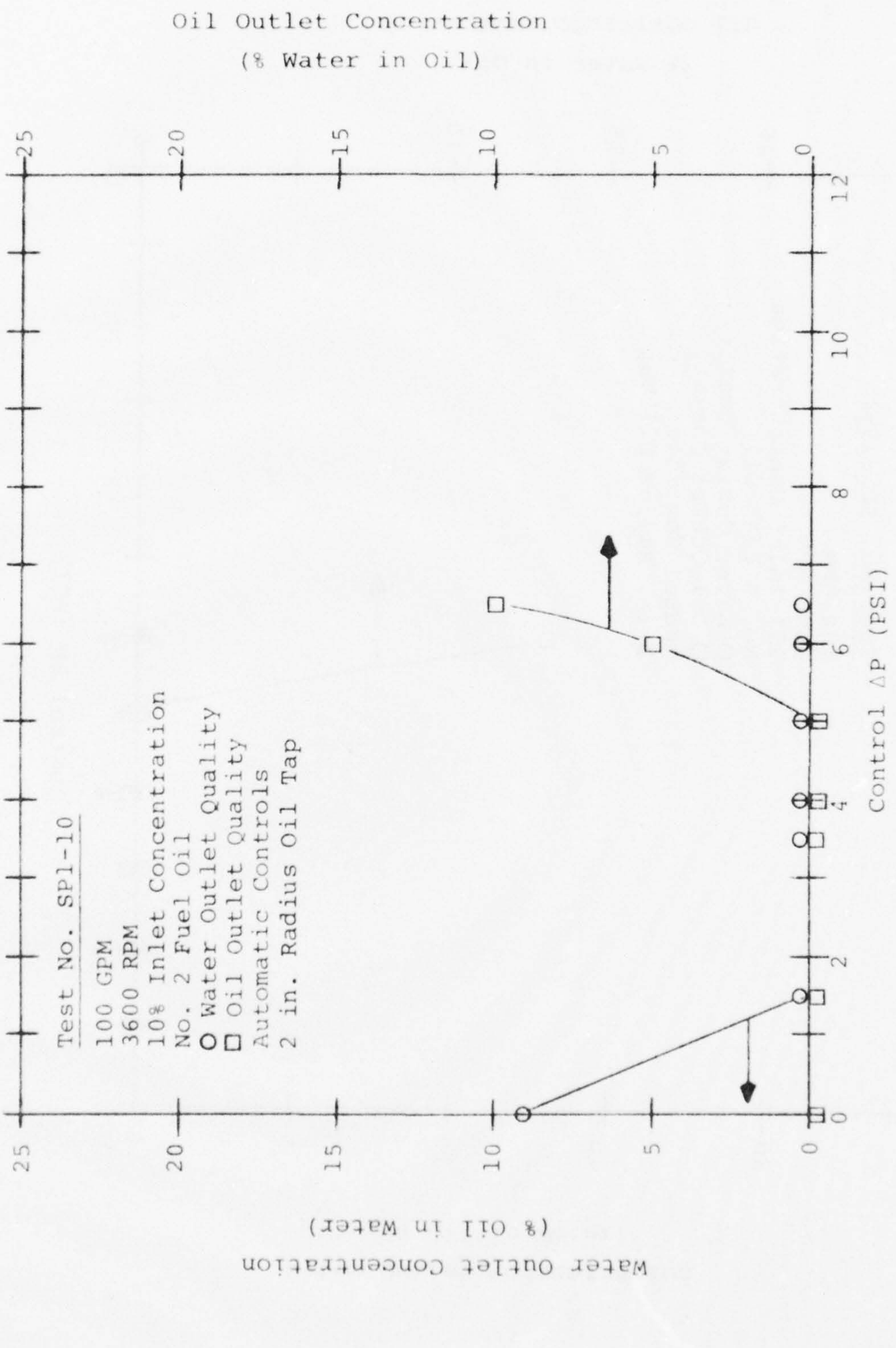


Figure 5-1. Outlet Concentrations Versus Control ΔP For No. 2 Fuel Oil at 100 gpm and 10% Inlet Oil Concentration

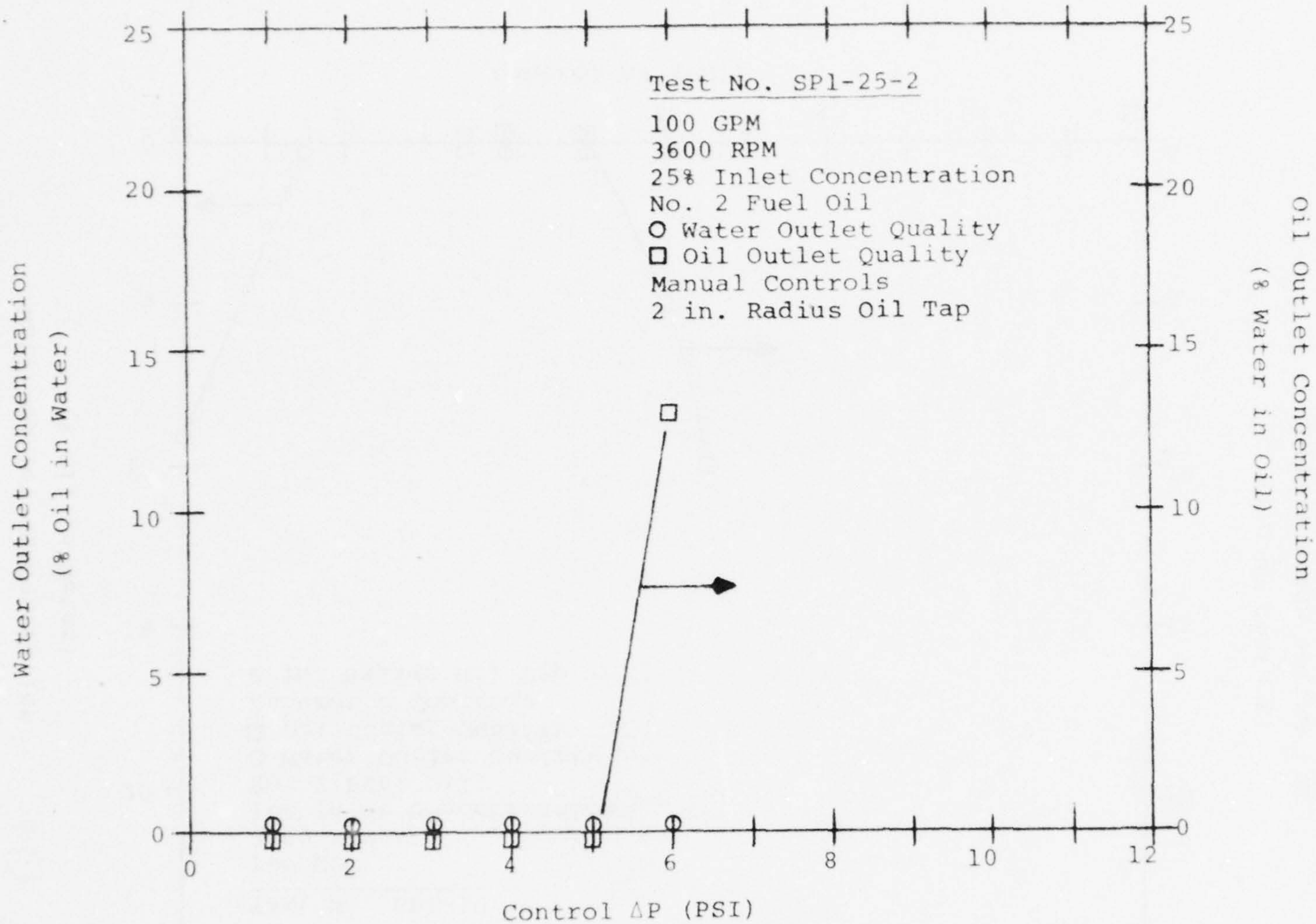


Figure 5-2. Outlet Concentration Versus Control ΔP For No. 2 Fuel Oil at 100 gpm and 25% Inlet Oil Concentration

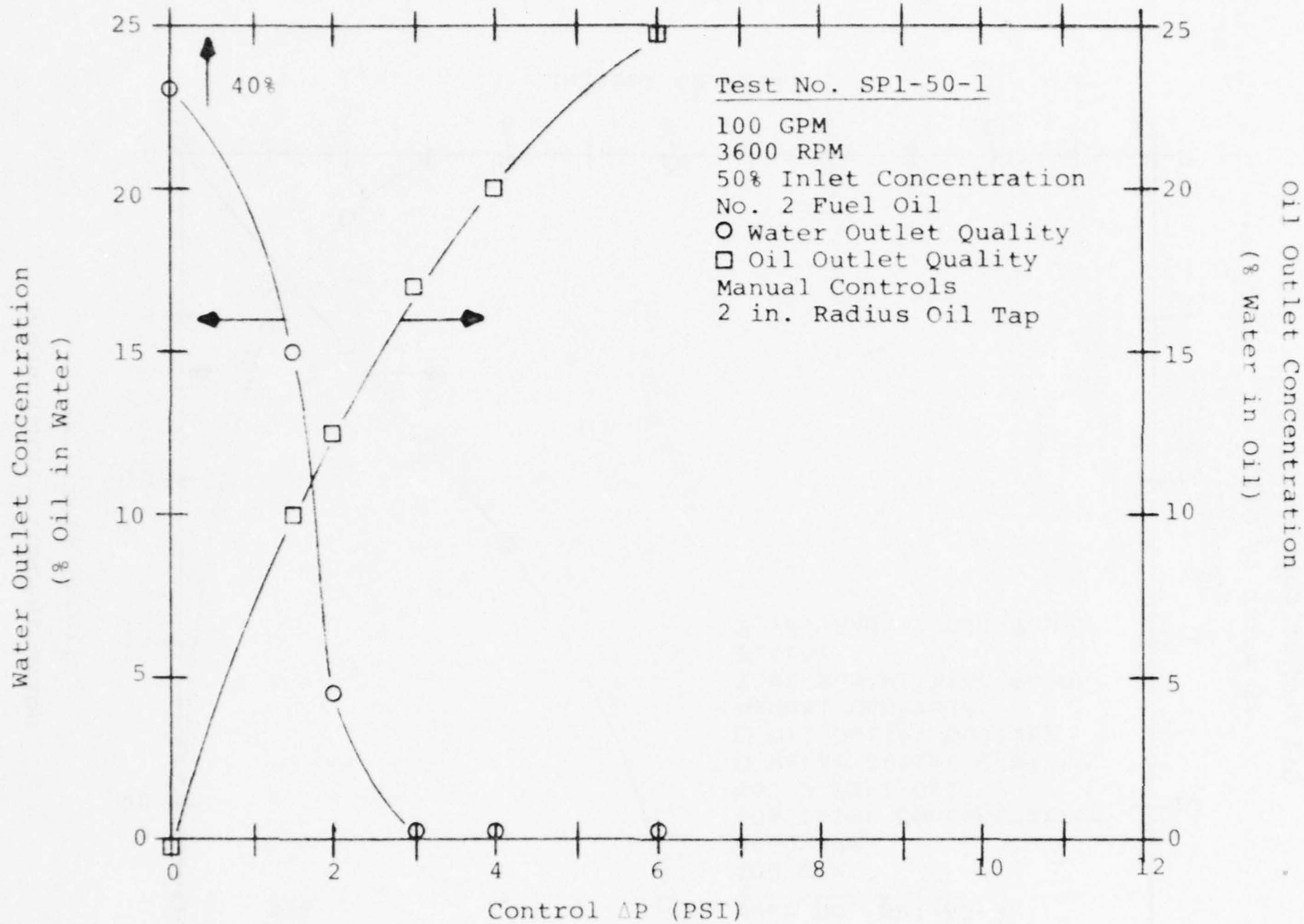


Figure 5-3a. Outlet Concentration Versus Control ΔP For No. 2 Fuel Oil at 100 gpm and 50% Inlet Oil Concentration

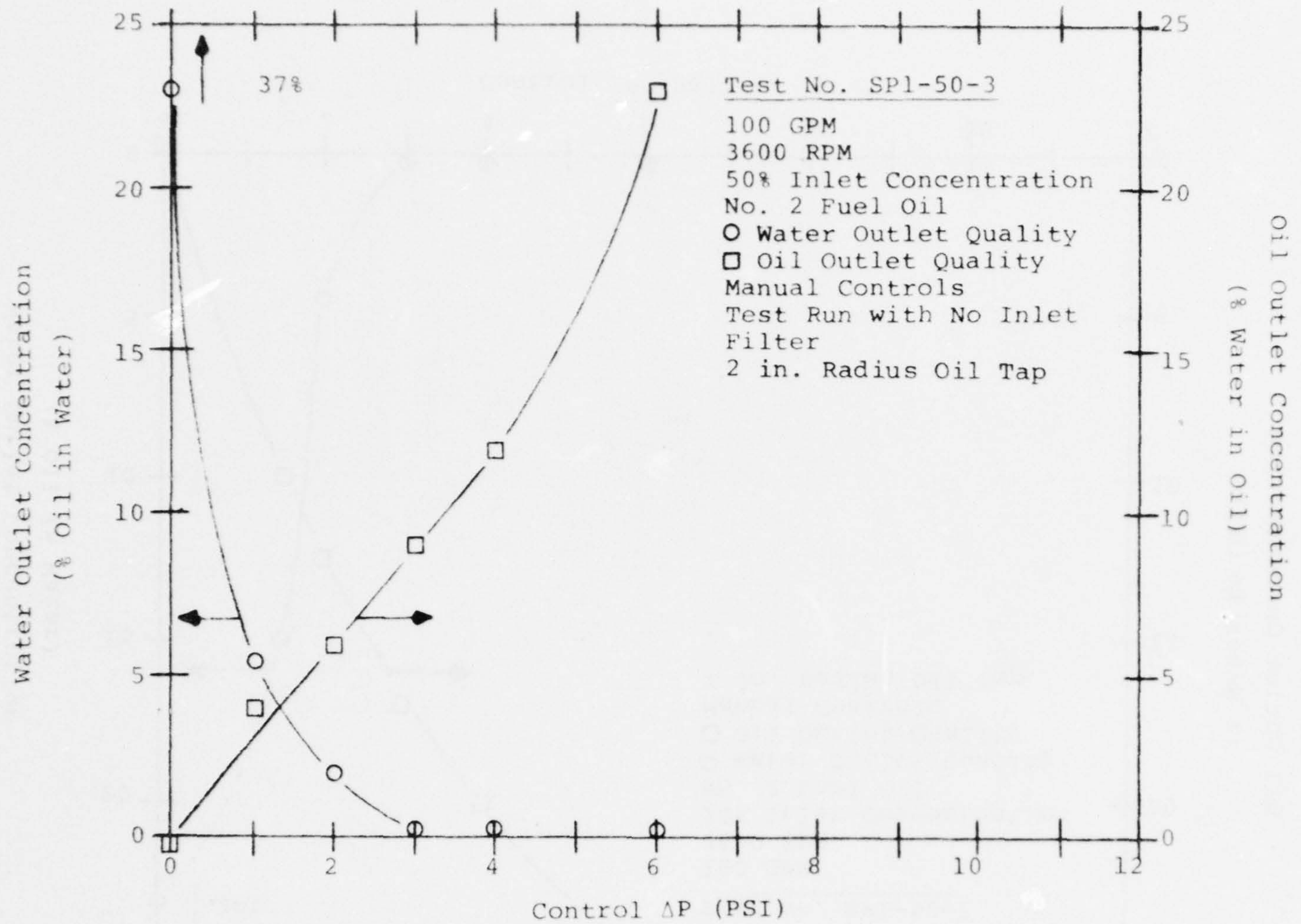


Figure 5-3b. Outlet Concentrations Versus Control ΔP For No. 2 Fuel Oil at 100 gpm and 50% Inlet Oil Concentration With Inlet Filter Removed

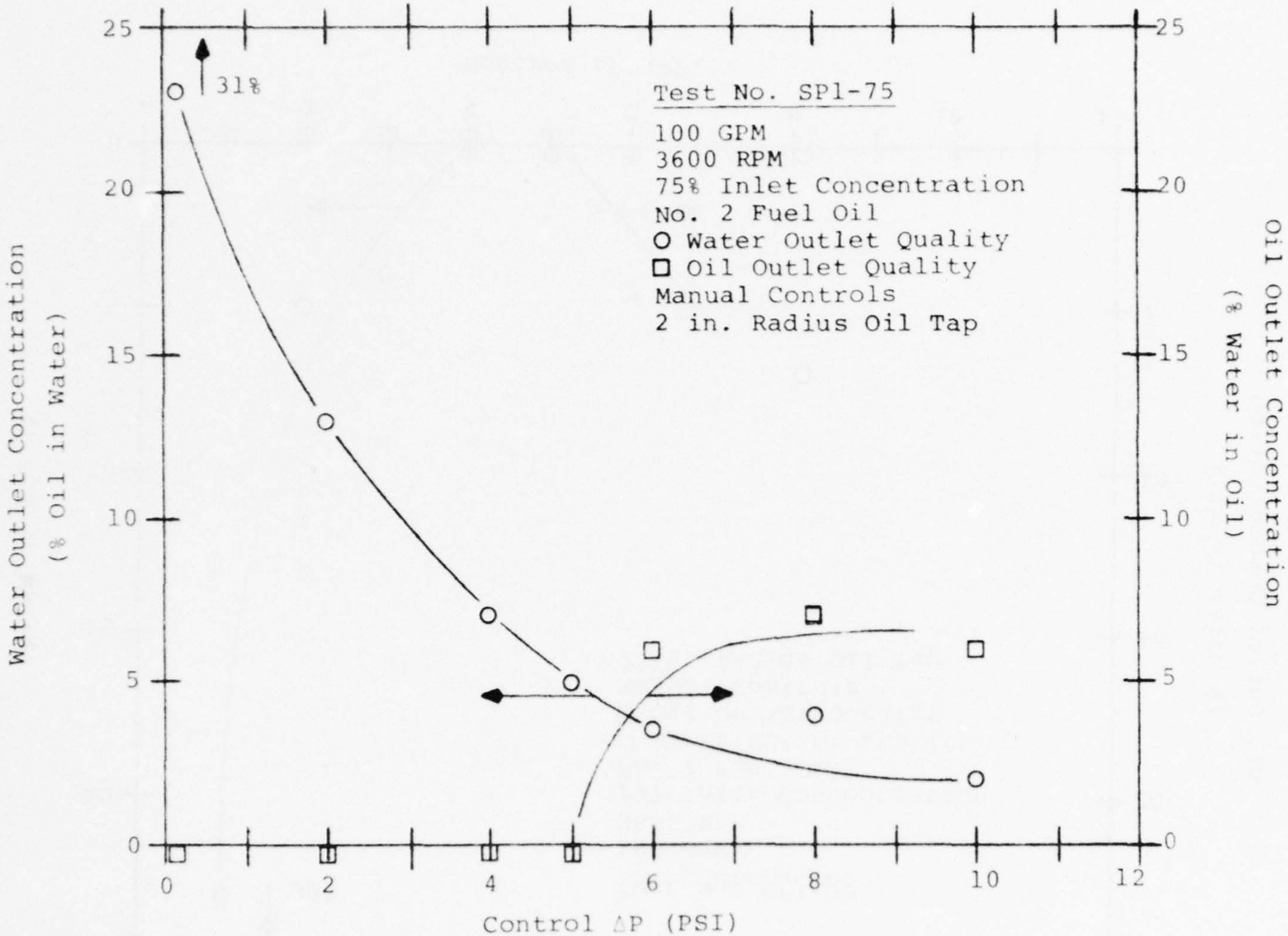


Figure 5-4. Outlet Concentrations Versus Control ΔP For No. 2 Fuel Oil at 100 gpm and 75% Inlet Oil Concentration

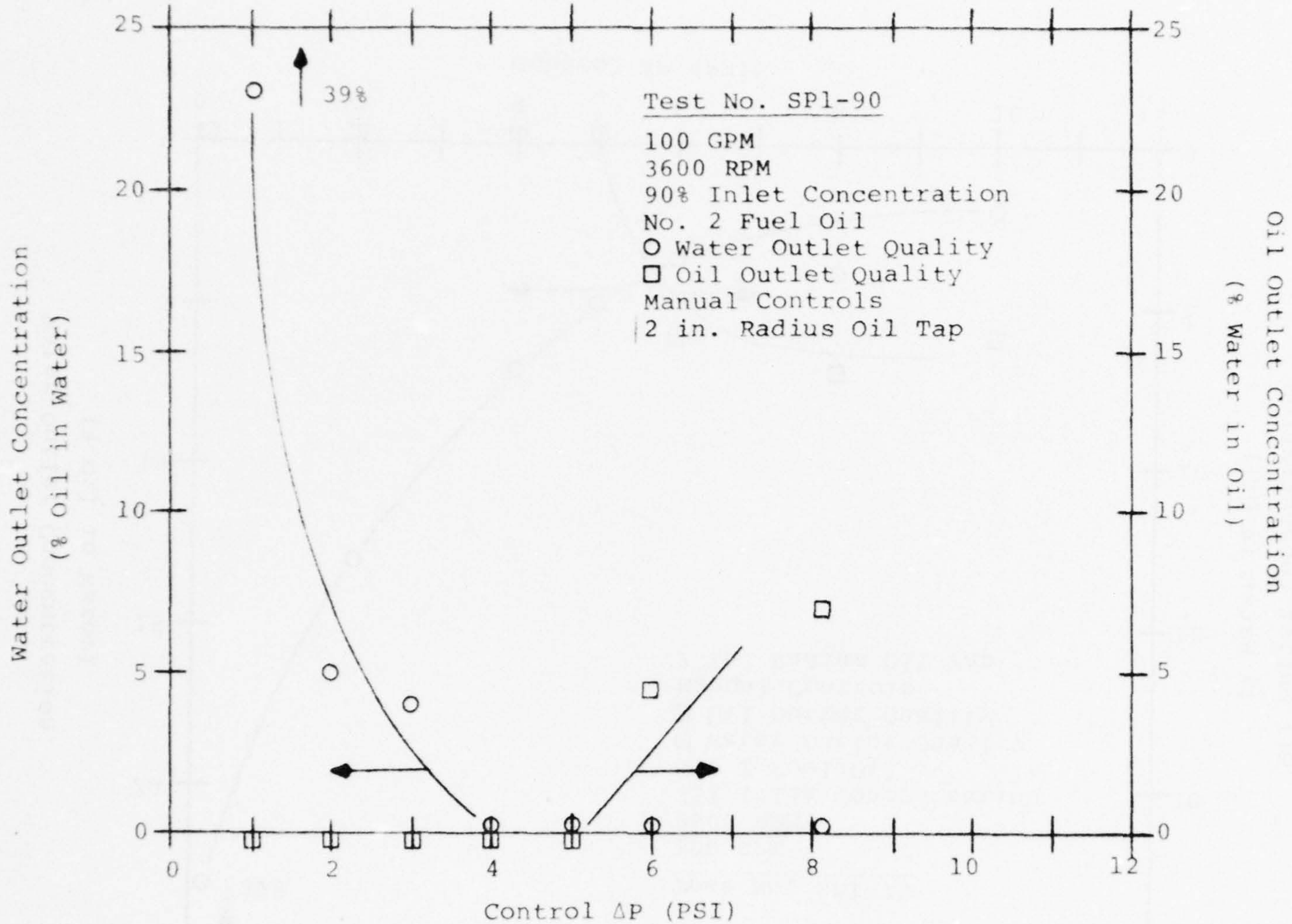


Figure 5-5. Outlet Concentrations Versus Control ΔP For No. 2 Fuel Oil at 100 gpm and 90% Inlet Oil Concentration

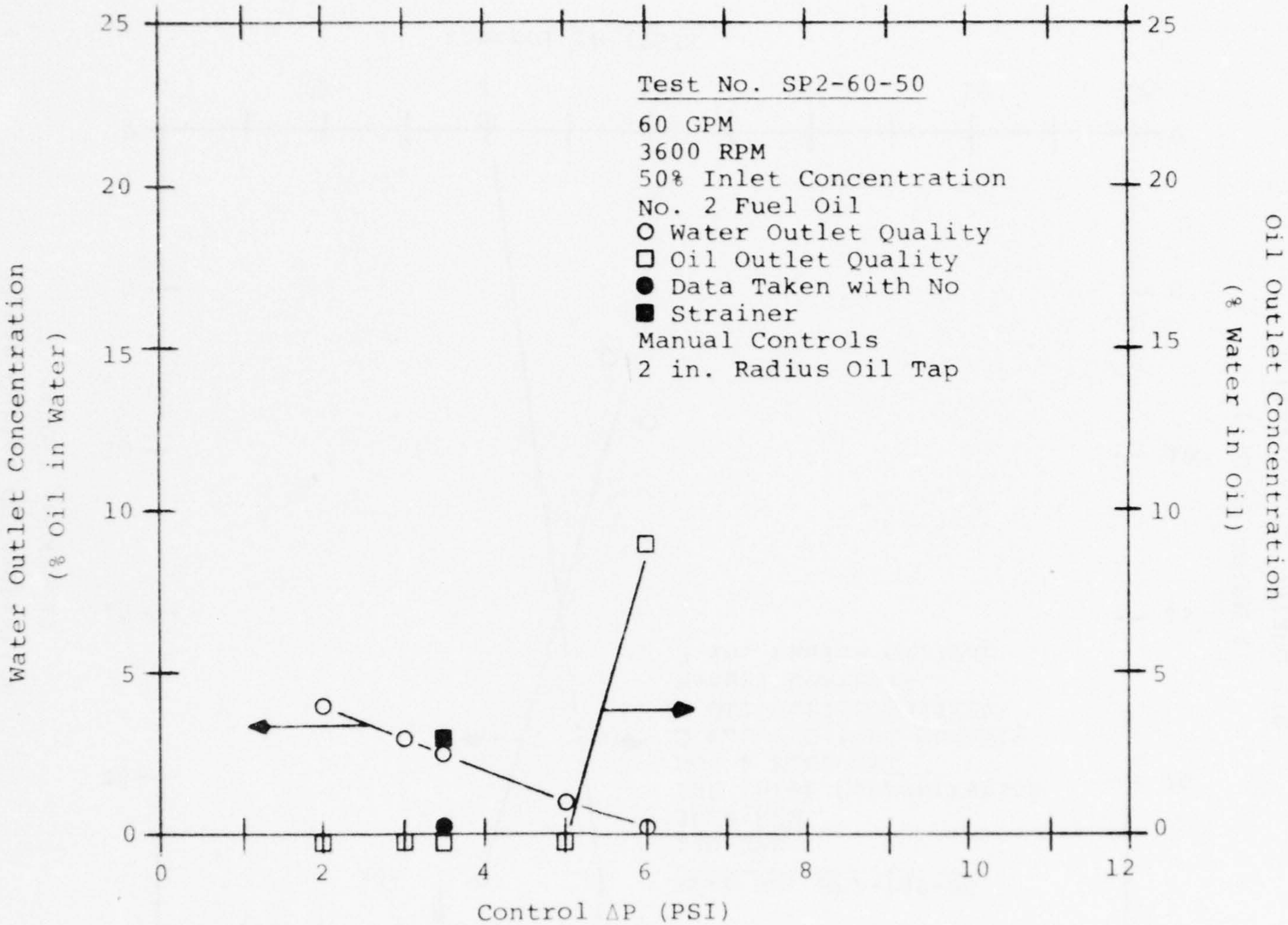


Figure 5-6. Outlet Concentrations Versus Control ΔP For No. 2 Fuel Oil at 60 gpm and 50% Inlet Oil Concentration

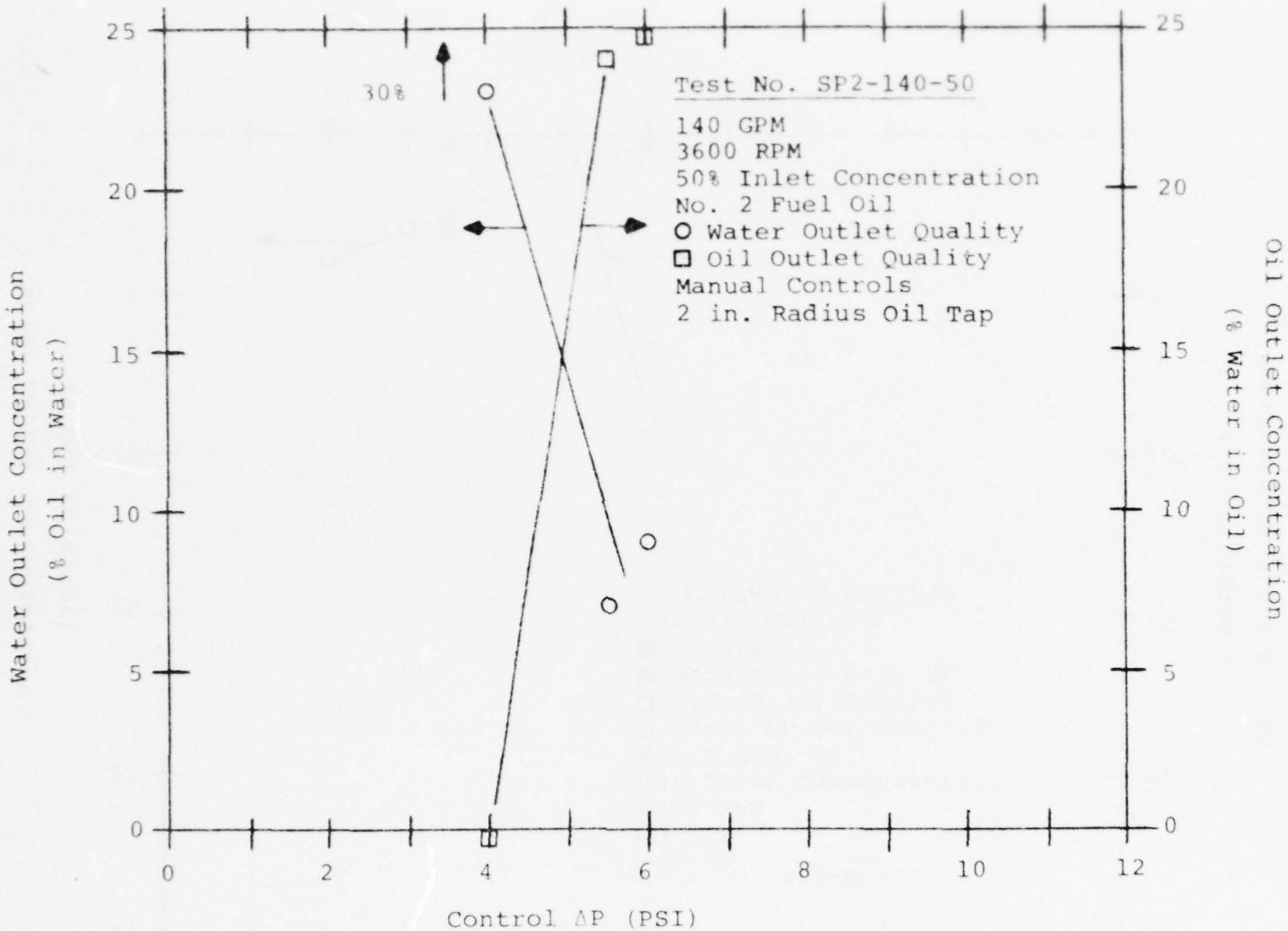


Figure 5-7a. Outlet Concentrations Versus Control ΔP For No. 2 Fuel Oil at 140 gpm and 50% Inlet Oil Concentration

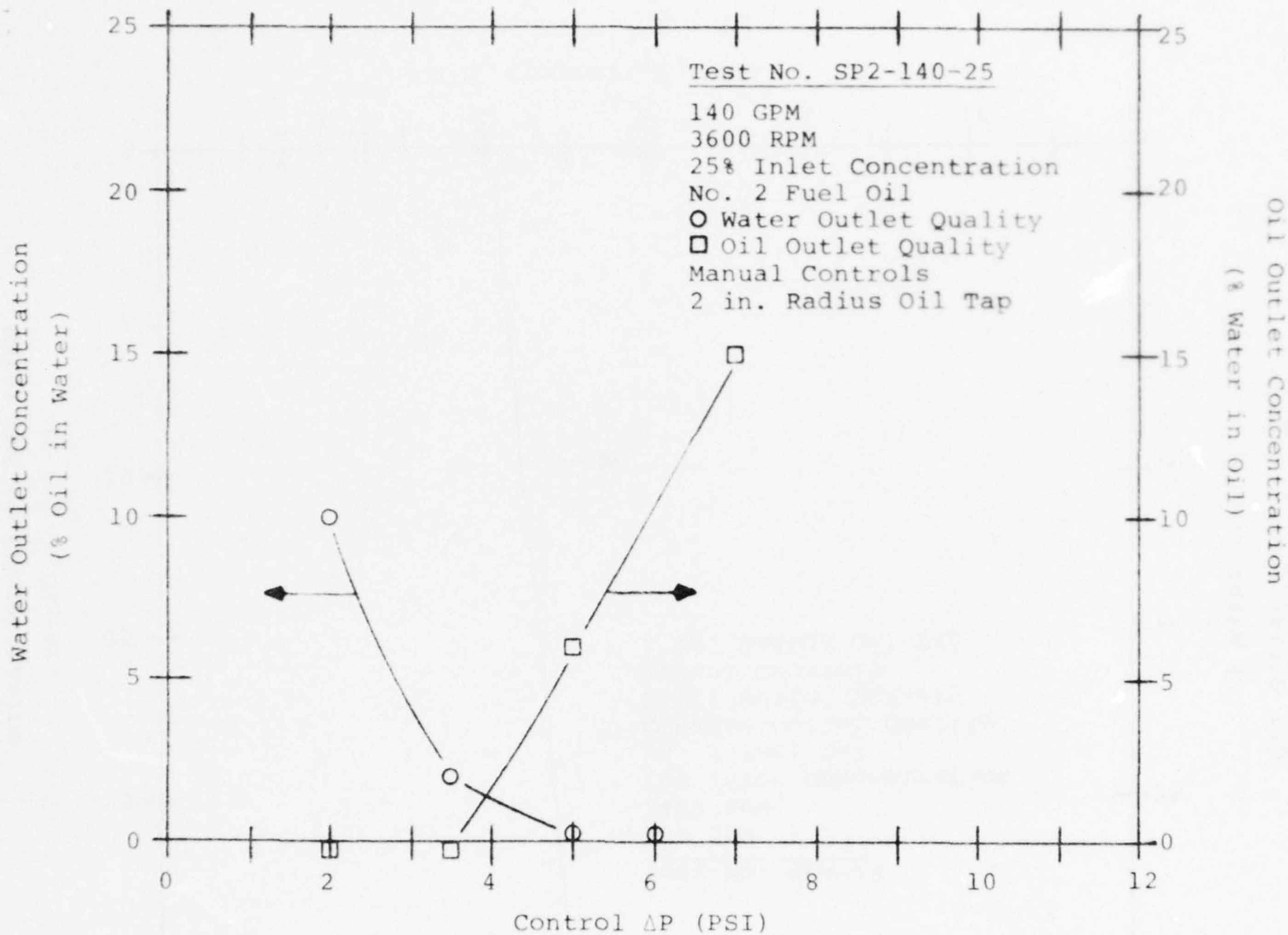


Figure 5-7b. Outlet Concentrations Versus Control ΔP For No. 2 Fuel Oil at 140 gpm and 25% Inlet Oil Concentration

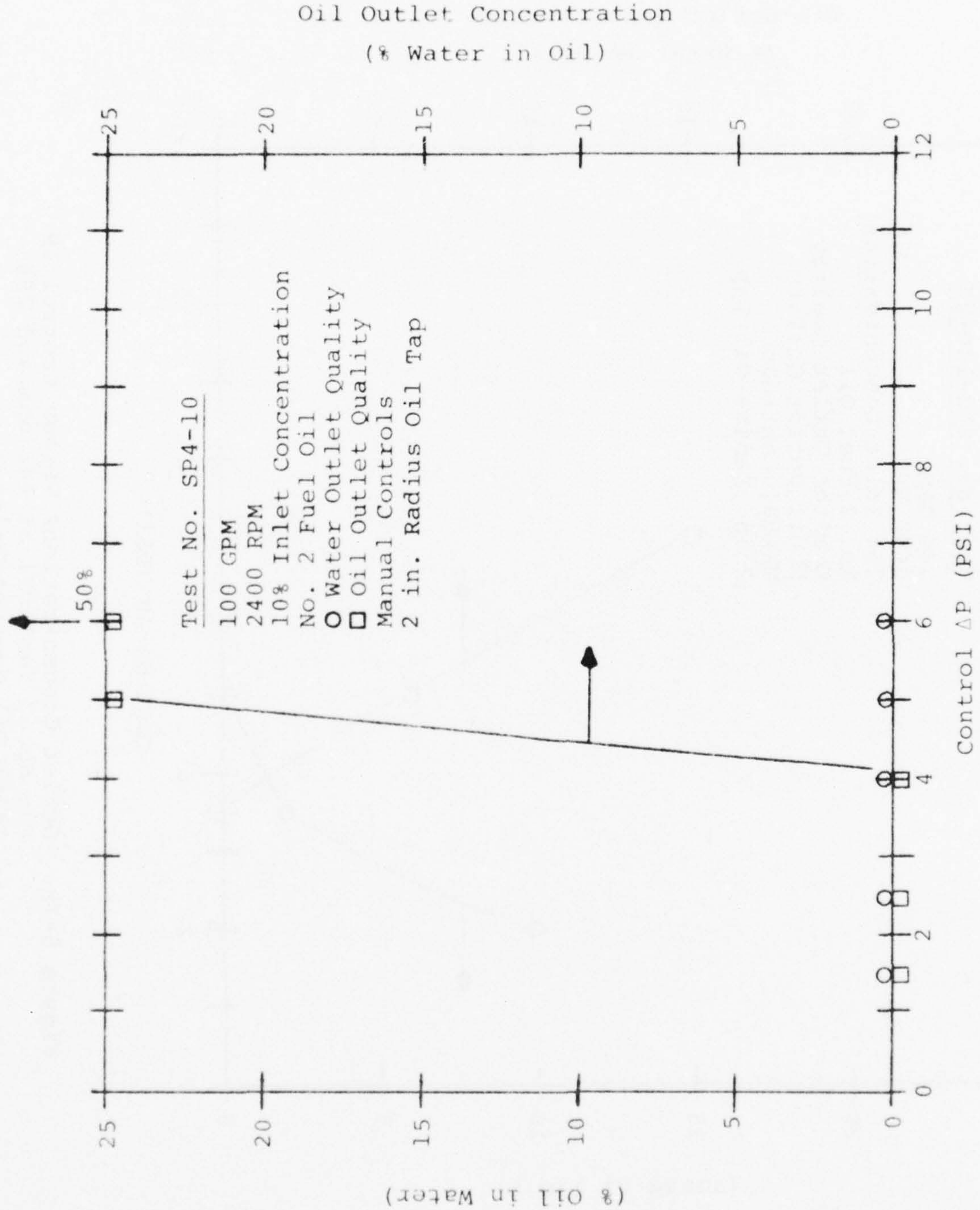


Figure 5-8. Outlet Concentrations Versus Control ΔP For No. 2 Fuel Oil at 2400 rpm, 100 gpm and 10% Inlet Oil Concentration

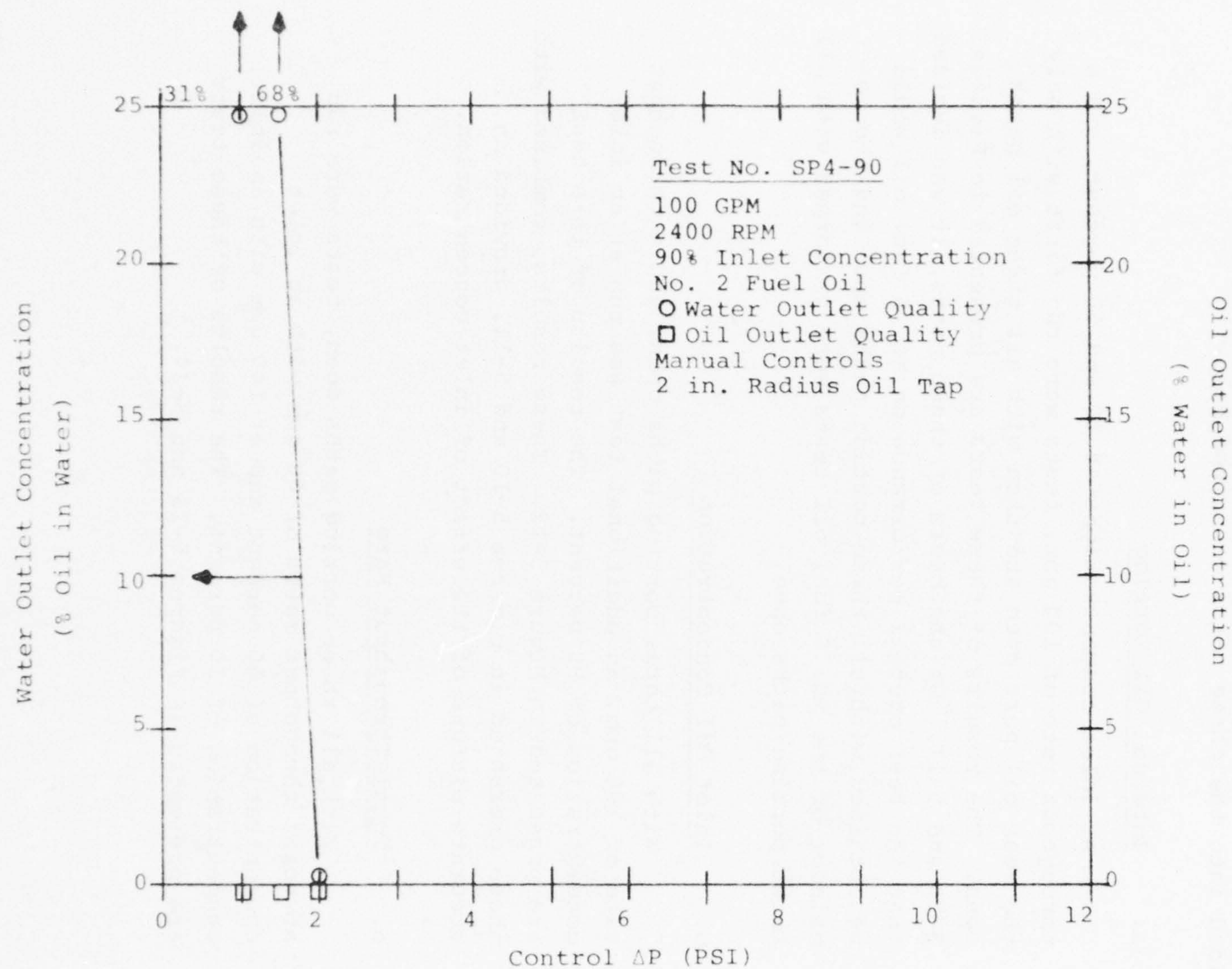


Figure 5-9. Outlet Concentrations Versus Control ΔP For No. 2 Fuel Oil at 2400 rpm, 100 gpm and 90% Inlet Oil Concentration

rpm and at an inlet pressure of zero psig. These tests were divided into the three parts described below:

a. Internal Oil Porting

At inlet concentrations of 10 and 50 percent, and a throughput rate of 100 gpm, tests were run first with only the rear oil port open and then with all three oil paths open. The results of these tests are presented in Figures 5-10 and 5-11. On the basis of these tests, it was decided that the best overall performance on No. 6 fuel oil would be obtained with all three porting paths open and the remainder of the No. 6 fuel oil tests were performed with all three porting paths open.

b. Inlet Oil Concentration

With all three porting paths open, and a throughput rate of 100 gpm, an additional test was run at an inlet concentration of 90 percent. The results of this test are presented in Figure 5-12. These results, combined with those presented in Figures 5-10 and 5-11, provided an accurate picture of the effect of inlet concentration.

c. Total Throughput Rate

With all three porting paths open, tests were run at total throughput rates of 60 gpm with an inlet concentration of 50 percent and at 140 gpm with an inlet concentration of 10 percent. The results of these tests are presented in Figures 5-13 and 5-14.

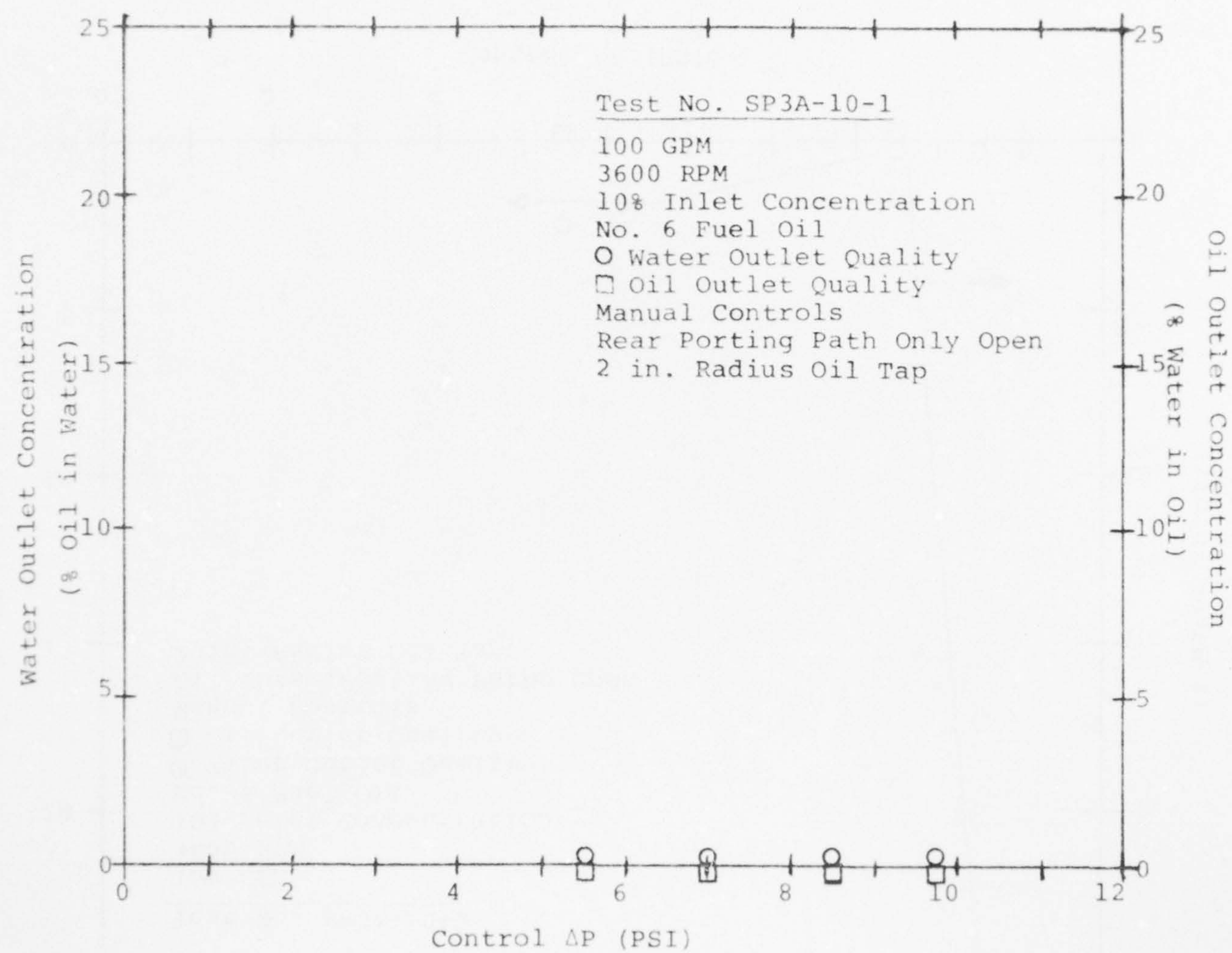


Figure 5-10a. Outlet Concentrations Versus Control ΔP For No. 6 Fuel Oil at 100 gpm and 10% Inlet Oil Concentration with Rear Porting Path Open

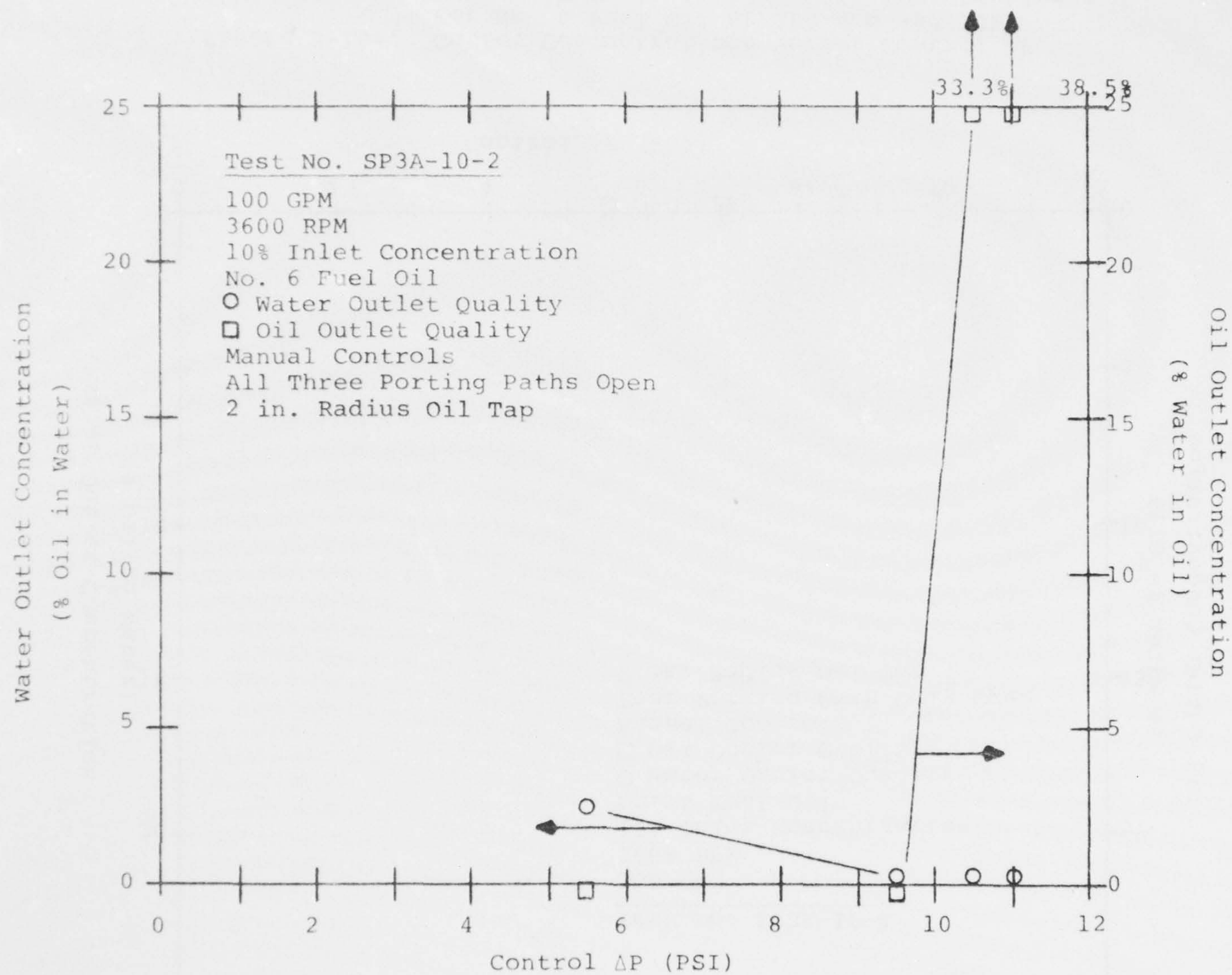


Figure 5-10b. Outlet Concentration Versus Control ΔP For No. 6 Fuel Oil at 100 gpm and 10% Inlet Oil Concentration with all Three Porting Paths Open

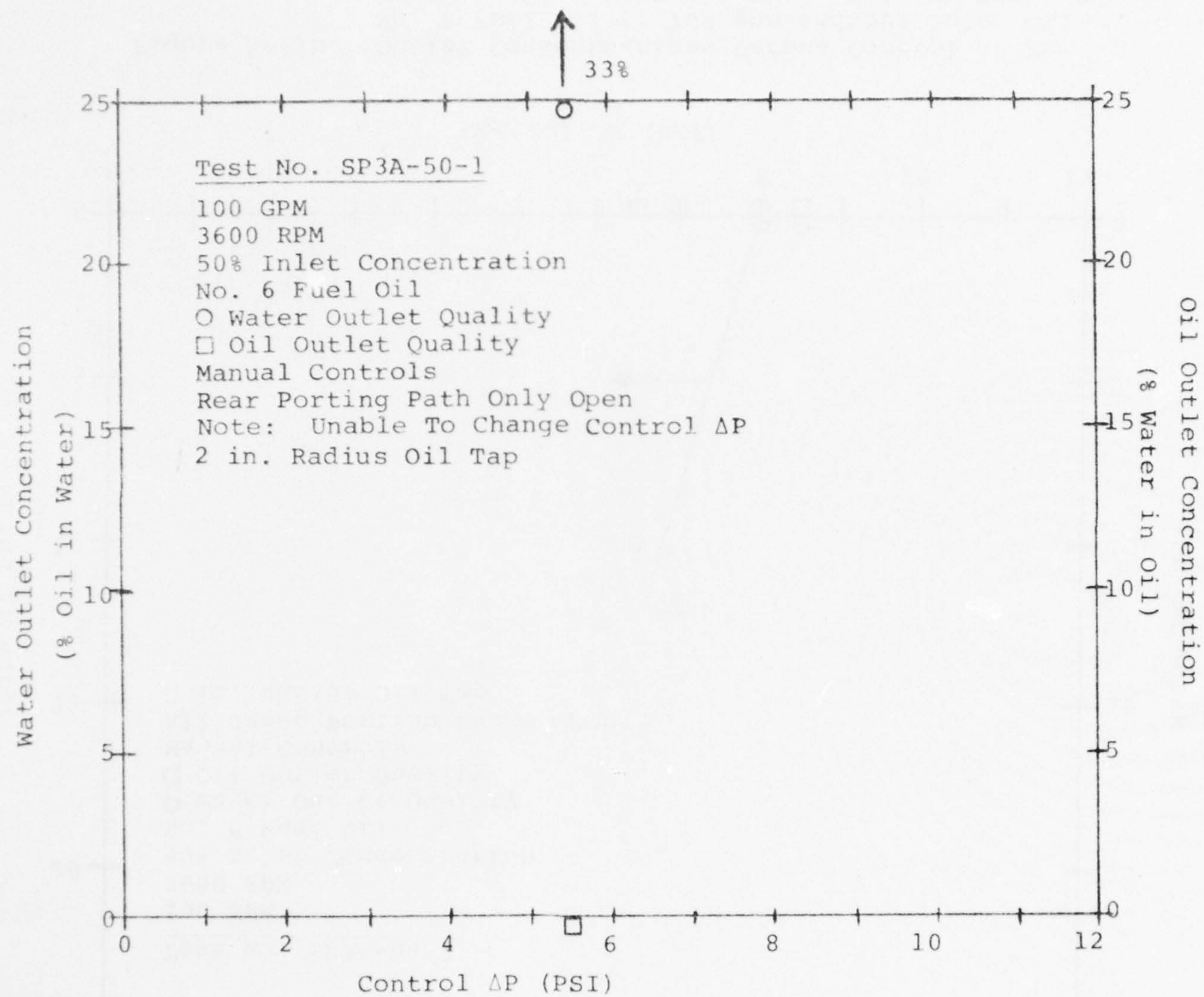


Figure 5-11a. Outlet Concentrations Versus Control ΔP For No. 6 Fuel Oil at 100 gpm and 50% Inlet Oil Concentration with Rear Porting Path Open

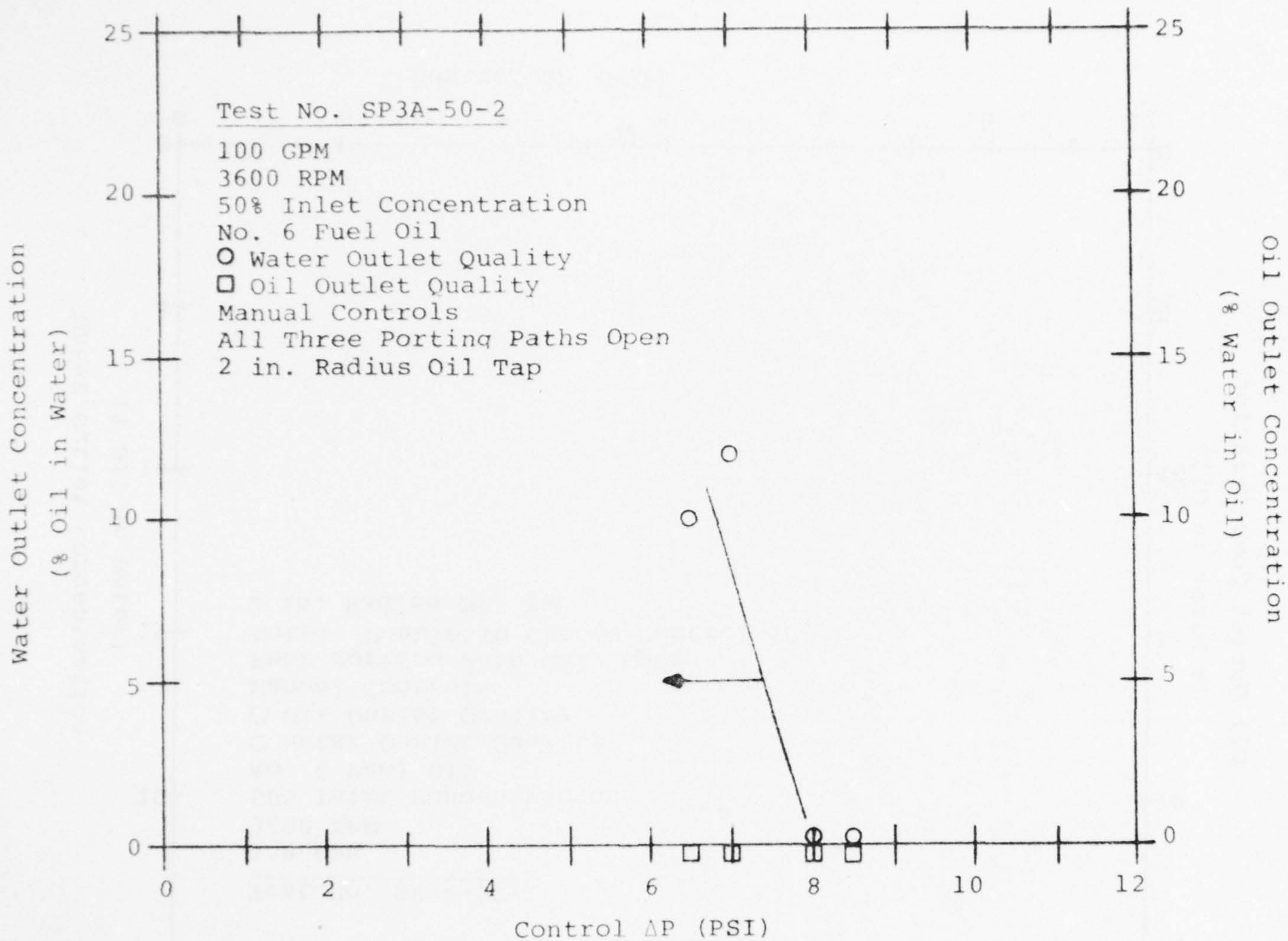


Figure 5-11b. Outlet Concentrations Versus Control ΔP For No. 6 Fuel Oil at 100 gpm and 50% Inlet Oil Concentration With All Three Porting Paths Open

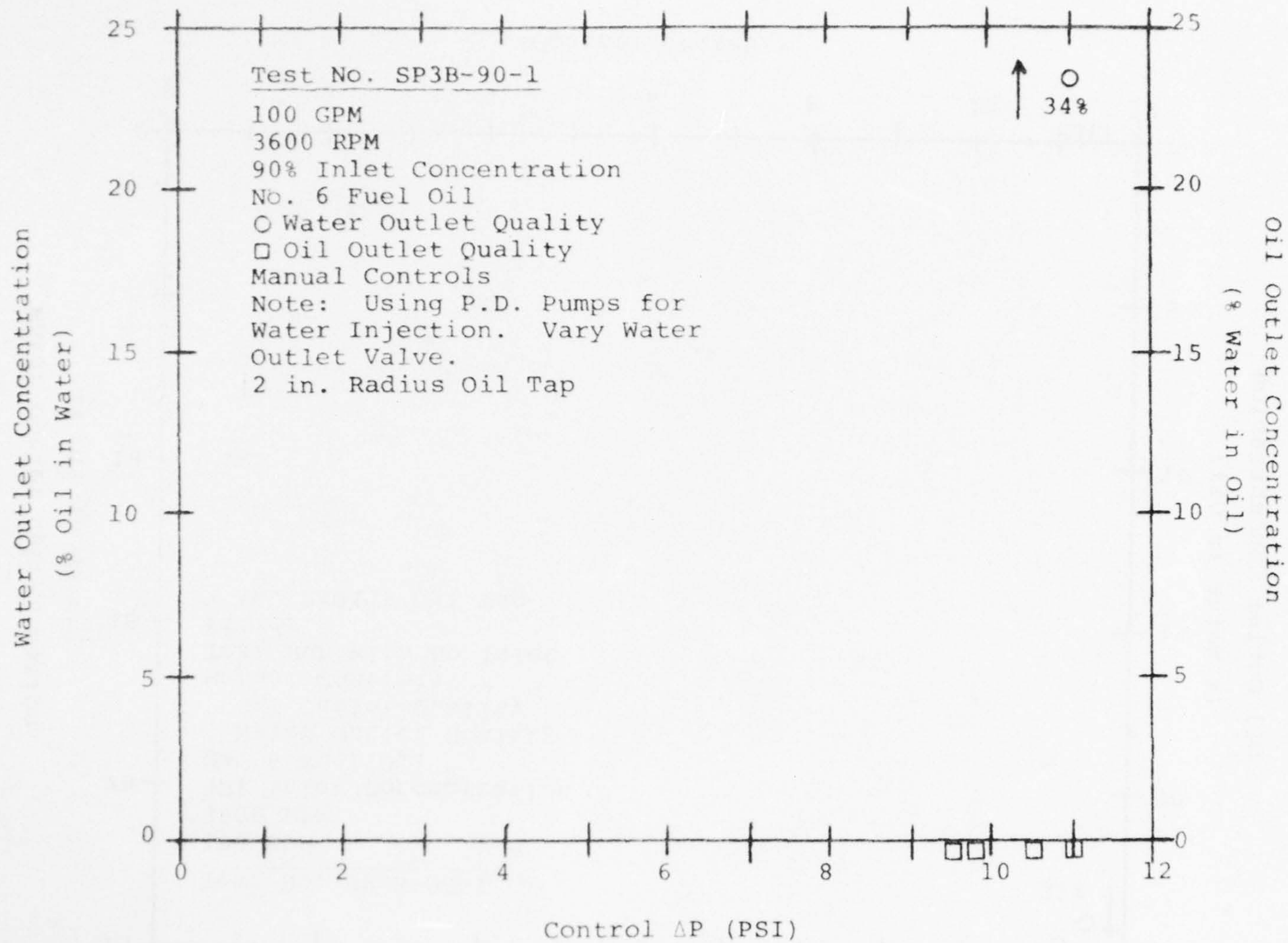


Figure 5-12a. Outlet Concentrations Versus Control ΔP For No. 6 Fuel Oil at 100 gpm and 90% Inlet Oil Concentration with all Three Porting Paths Open

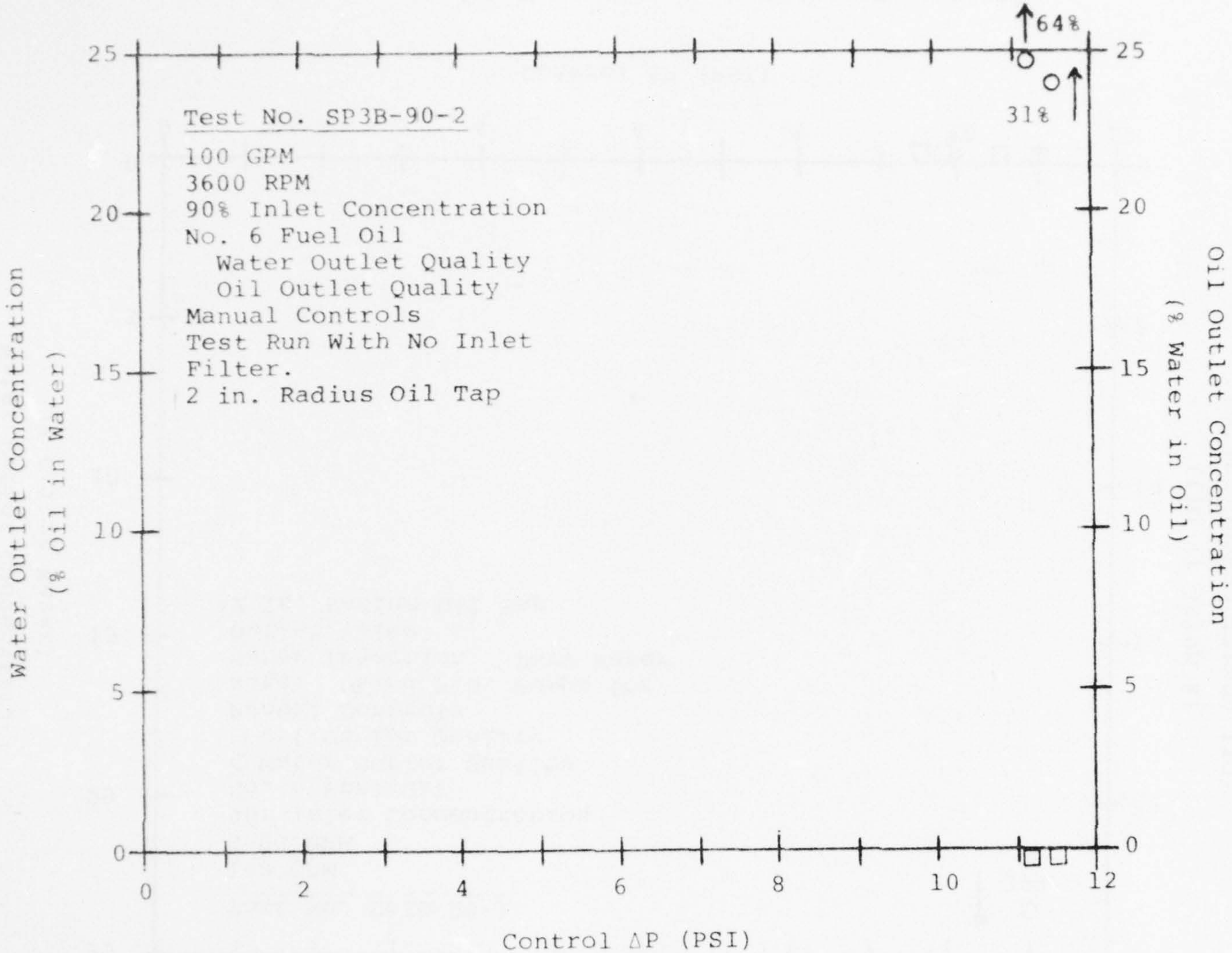


Figure 5-12b. Outlet Concentrations Versus Control ΔP For No. 6 Fuel Oil at 100 gpm and 90% Inlet Concentration With All Three Porting Paths Open

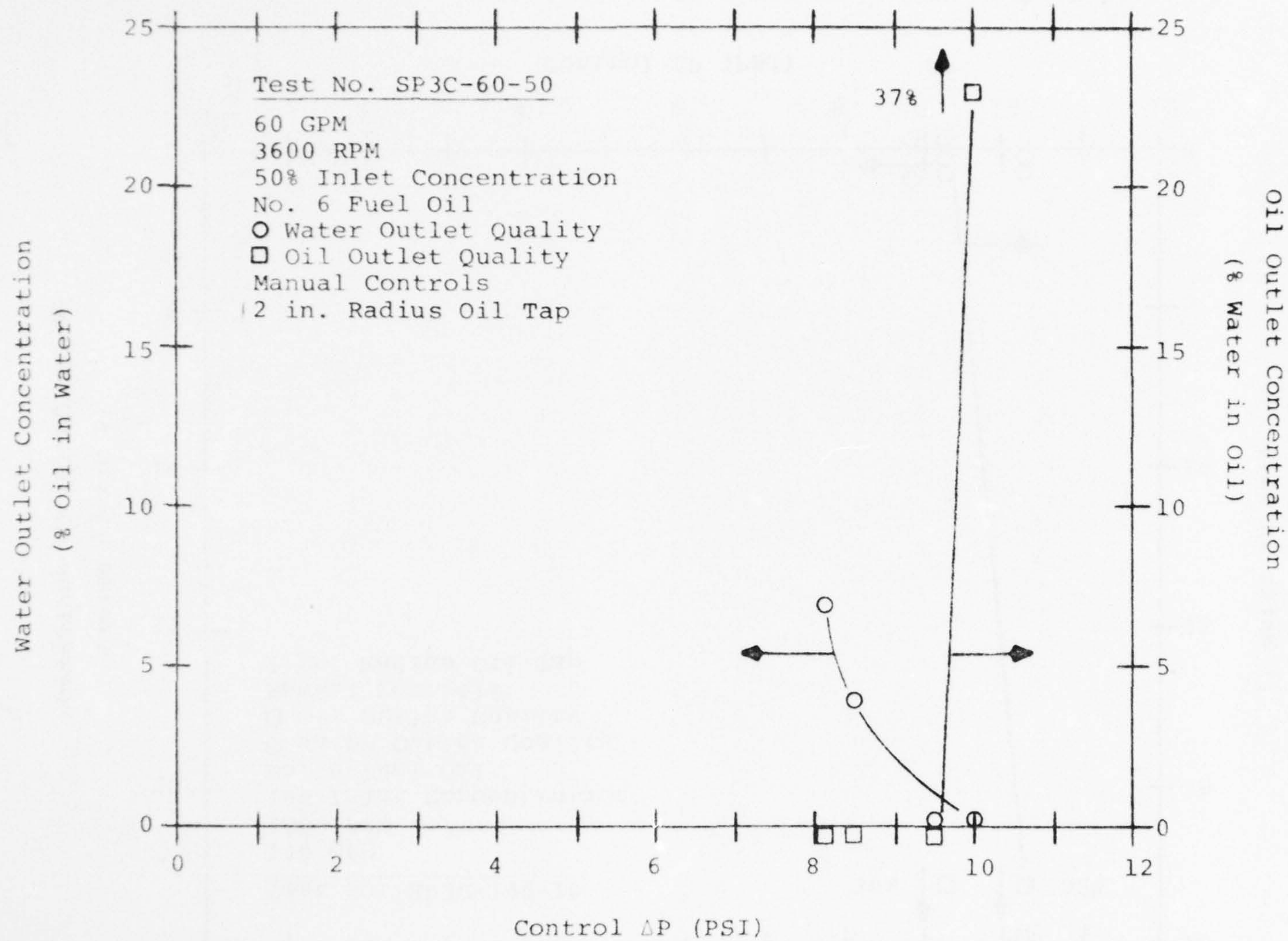


Figure 5-13. Outlet Concentrations Versus Control ΔP For No. 6 Fuel Oil at 60 gpm and 50% Inlet Oil Concentration With All Three Porting Paths Open

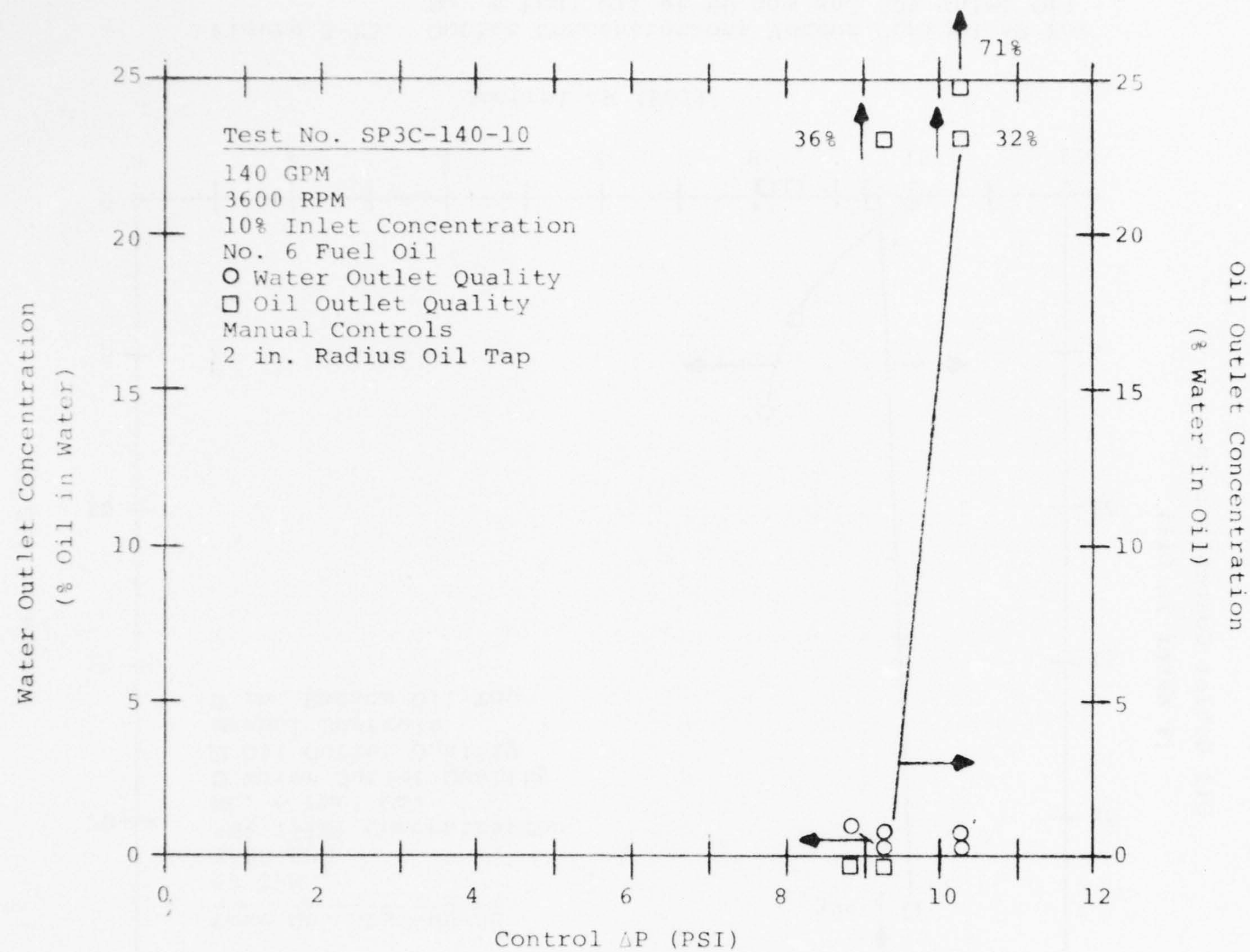


Figure 5-14. Outlet Concentrations Versus Control ΔP For No. 6 Fuel Oil at 140 gpm and 10% Inlet Oil Concentration With All Three Porting Paths Open

6. CONCLUSION

On the basis of the testing performed on the Spilled Oil Recovery Separator and the automatic effluent discharge controls, the conclusions presented in the following paragraphs may be drawn. For clarity, these conclusions are divided into three parts.

a. Fluid Mechanical Performance

b. Automatic Effluent Discharge Controls

c. Separation Performance

6.1 Fluid Mechanical Performance

On the basis of the fluid mechanical testing performed, the following conclusions about the Spilled Oil Recovery Separator may be drawn. These conclusions are divided into the same five areas in which the data was presented in Section 4.

6.1.1 Pumping Performance

The separator is capable of pumping 100 gpm total throughput, with any flow distribution; and providing any oil outlet pressure ranging from 40 to 50 psi above inlet, and a water outlet pressure ranging from 28 to 36 psi above inlet.

6.1.2 Suction Performance

The separator is capable of pumping 100 gpm total throughput with any flow distribution at inlet pressures as low as 20 inches of Mercury vacuum (-10 psig).

6.1.3 Horsepower Requirements

The motor horsepower required by the separator for any of the above pumping ranges from 6.7 to 8.1 horsepower.

6.1.4 Control Pressure Behavior

For best operation of the control system, the control pressure differential between oil and water taps should be independent of all flow conditions except the position of the oil-water interface in the rotor (given speed and specific gravity difference). Judging from all the data with water alone, light oil, and heavy oil, we believe the behavior of the pressure differential is adequate except under conditions of reduced inlet pressure combined with high oil flow, or with high flow of viscous oil. We believe the inadequacies can be removed with modifications of the outlet sections of the separator.

6.1.5 Air Ingestion

The separator is capable of processing only small amounts of air with no degradation in performance.

6.2 Automatic Effluent Discharge Controls

On the basis of the testing performed on the automatic effluent discharge controls, the following conclusions may be drawn:

a. The concept of controlling the oil and water discharge flow rates by pilot valves, which sense the level of the internal oil pool and activate flow control valves, has been successfully demonstrated on light and heavy oil.

b. The initial method of utilizing commercially available control valves was demonstrated to meet many performance requirements. However, the operation of these valves was not maintained from one day to the next, even on light oil. Operation on heavy oil was unsuccessful.

The problems which appear to be responsible for this highly unpredictable operation of the automatic control valves may be summed up as follows.

a. Rapid oil control valve motion caused fluctuations in the flow rate and inlet concentration that became amplified in a cyclic manner in the laboratory flow loop.

b. Air accumulated in the rotor core and more than likely migrated into the control plumbing. The presence of this air contributed to the erratic, undamped control valve motion.

c. The erratic control valve motion, aggravated by air in the rotor core, resulted in extreme fluctuations in inlet and outlet pressures when positive displacement pumps were being used to supply the separator. When the separator was drawing its own suction, this erratic control valve motion caused large flow ranges and occasionally complete loss of flow due to air lock.

d. Sudden and non-synchronous motions of the oil and water control valves could cause the separator to air-lock or the water discharge to flood with oil, causing the control pressure signal to change perversely and usually requiring manual flow control for restart.

e. The response was too slow with heavy oil.

6.3 Separation Performance

Performing goals for the machine are to separate 95 percent of the oil in its influent, and to discharge this oil containing less than 10 percent water. Water discharge cleanliness is not a specific goal for spilled oil recovery.

Extensive testing with light oil (No. 2 fuel oil) shows that with either automatic control or manual control the performance goals can be met, and that best overall performance is obtained if the control pressure differential is maintained in a small range, consistent with theory for the oil-water level in the rotor.

At 3600 rpm and 100 gpm, the separator clearly exceeds performance goals except if the input concentration is 50 percent. This is with a control pressure differential of 2 to 4 psi (2 inch radius oil tap). At 50 percent concentration, goals may or may not be met. They have been exceeded occasionally with stable automatic control. At low input oil concentration, good performance is maintained up to at least 140 gpm. At 60 gpm, performance is excellent even at 50 percent concentration.

Performance at 2400 rpm is respectable but probably does not meet goals at 50 percent concentration. This low speed operation does not appear to be advantageous, particularly with respect to output and control pressures, but the overall performance does indicate that the machine is not sensitive to speed variations near the design level, 3600 rpm.

Limited testing with heavy oil (No. 6 fuel oil at room temperature) showed two things clearly: the performance of the machine was either poor or questionable, compared to goals; and, the conducting of continuous recirculating tests with heavy oil was difficult. All tests were run with manual control of oil and water discharge flows, and although satisfactory separation could be obtained at some conditions, the control pressure differential

was anomalous. Without question, a major source of difficulty in achieving separation and interpreting results was the fact that oil supply accumulated stable dispersed water, and also the water supply quality deteriorated during recirculation.

However, considering the favorable factors, we can say that in some tests at 100 gpm, 3600 rpm, and input concentrations of 10, 50, and 90 percent, the separation performance goals were met with respect to "free" water and oil in the discharge flows (free, meaning that which will separate by normal gravity in a day or two). Separation at 50 percent concentration was better with all ports open in the rotor core. Separation was also better over a larger range of control pressure at 60 gpm. Separation was good with a wide control pressure range at 100 gpm, 10 percent concentration, and good in a narrow range at 140 gpm.

Near the end of testing with the heavy oil, it was encouraging that the machine still separated the input at all, because the "oil" injected actually contained nearly 50 percent emulsified water. This caused the apparent oil viscosity to be several times that of the original oil, and the specific gravity difference between the apparent oil and water inputs to be very small. (Specific gravity: new oil, 0.93; used oil, 0.975.) Centrifuges are not normally expected to function well with these fluid conditions.

Considering the unfavorable aspects of heavy oil testing, we consider emulsification and anomalous control pressures most important. Emulsification may be caused primarily by recirculation testing at set points offering poor oil-water separation, or it may be primarily due to churning in the separator inlet. The former is *not* a problem in once-through operation of a properly controlled machine; the latter is. Control pressure did not usually vary according to theory, even considering the apparent change in oil density. From detailed study of all the pressure data for the machine, we conclude that anomalous behavior

was due to excessive pressure loss in the rotor oil outlet tube, possibly aggravated by effective oil plugging of the air bleed hole, and poor response of the pressure gauges and plumbing.

In summary, we believe that the separator can be developed to operate well on almost all oils that will float and can be skimmed and pumped effectively.

7. RECOMMENDATIONS

On the basis of the effort performed under this contract, FMA makes the following recommendations concerning the Spilled Oil Recovery Separator. These recommendations are divided into the five different areas listed below.

a. Test Loop

b. Mechanical Design

c. Fluid Mechanical Performance

d. Automatic Control

e. Separation Performance

7.1 Test Loop

Prior to the performance of any additional testing of the Spilled Oil Recovery Separator, FMA recommends the following additions to the test loop.

a. Installation of positive displacement type flow meters on both supply lines and on the water outlet line. The current rotometer is difficult to read and is only accurate with water and light oil. Better flowmeters will facilitate stabilizing test points, particularly with high concentrations of heavy oil.

b. Installation of a heater-coalescer unit to reprocess off-stream heavy oil containing emulsified oil. Opertion of the recirculating test loop with heavy oil, particularly at sub-optimum control settings, leads to accumulation of emulsions formed in the separator

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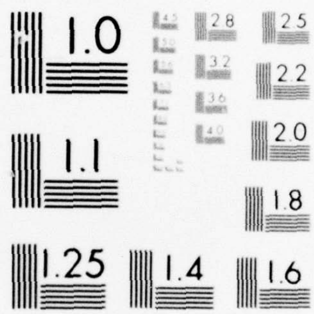

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discharge. These water-in-oil emulsions can have densities very near that of water and extremely high viscosity (also thixotropy). Recirculation is not typical of intended service, so either the emulsions must be broken or much more fresh oil used in testing.

7.2 Mechanical Design

On the basis of the experience gained disassembling and assembling the Spilled Oil Recovery Separator, FMA recommends the following modifications to the mechanical design of the separator.

a. Change several sealing O-rings between the rotor sections and the housing sections to be face type seals rather than male gland type.

b. Modify the rotor outlet tubes, shaft, and oil pumping rotor to be much shorter and offer less resistance to oil outflow and air purging with heavy oil.

c. Redesign the housing outlet section to accommodate the shorter rotor, provide easier assembly, offer more rigid, compact valve mounting, and reduce the cost, power, and complexity of the seals.

d. Modify the bearing system to put the axial load on the front bearing and eliminate the rear retaining nut.

e. Modify the inlet and outlet end bell design to allow for recessing of the bolt heads. This change would reduce the noise level of the machine.

f. Addition of locating pins on all critical part orientations. Notably these pins should be installed between the inlet end bell and the outer shield, between the outer shield and the outlet end bell, between the outlet housing and the outlet housing end cap, and between the shaft and the outlet end bell.

7.3 Fluid Mechanical Performance

As a result of the fluid mechanical testing performed, FMA recommends these additions or modifications to the Spilled Oil Recovery Separator:

a. Design and installation of a check valve for use on the shaft air bleed. This check valve could be designed to locate internal to the separator on the shaft or could be designed to locate external to the separator behind the rear shaft seal. Installation of this check valve would stop the leakage of oil from the separator when operating under positive inlet pressure and would allow the unit to be driven directly rather than by belts and pulleys.

b. Design and installation of a modified inlet tube and inducer to reduce inlet churning at 100 gpm and to improve the capabilities of the separator to ingest and process air. This addition would decrease the chances of an air-lock in the separator and would be a first step toward making the unit self-priming. This also should improve separation performance.

c. Modification of outlet diameter or installation of a pumping rotor on the water outlet side to improve the water pumping performance.

7.4 Automatic Controls

On the basis of the automatic effluent discharge controls testing, FMA strongly recommends further development in the area of automatic discharge control.

This improved control system should be designed to achieve maximum oil/water separation performance and roughly constant head-flow pumping performance. On the basis of test experience, the best separation performance will be obtained when the differential control pressure is held constant or nearly so. The head-flow characteristics will be roughly constant if the oil and water flow control valves open and close smoothly in opposition to each other, i.e., the oil valve opens while the water valve is closing and vice versa.

This improved control system should have the following features:

a. The ability to maintain the differential control pressure at a constant or nearly constant value, though this value may be set according to oil density.

b. A roughly constant total outlet flow.

c. The ability to operate on only one pilot flow system. This pilot loop should be located on the water discharge side and operate solely on water. This requirement minimizes the effect of oil viscosity and entrained air.

d. Leak-tight shutoff of the oil and water flow valves when that component is not present in the input. This requirement is especially important on the water side since some water must be maintained in the rotor in

order to maintain appropriate differential pressure control for a restart of the water flow.

In addition to the above features, it would be desirable, though not necessary, to have the control system to be relatively insensitive to centrifuge speed. With this feature it would not be necessary to closely control the speed of the driving motor and the centrifuge could even be used as a variable speed separating pump. The design solution of all these requirements has been studied and proposed separately.

7.5 Separation Performance

The recommendations given in Sections 7.3 and 7.4 are also significant in improving separation performance, particularly under varying operating conditions. In addition, the performance can be improved by optimizing the location of the oil drainage slots in the rotor inner tube, and by optimizing the radial height of the flow "dams" at the inlet and discharge ends of the separation zone. Separation performance can be improved with more number and area of slant vanes in the separation annulus, at some expense of more susceptibility to clogging and less flow rate with heavy oil. At least one other configuration should be tested to evaluate this.

8. BIBLIOGRAPHY

1. Department of Transportation - United States Coast Guard "Centriguge Coalescer Concept for Separating Oil from Water Discharged from Ships", Report No. 734305.2/3; Feb. 1973

2. Department of Transportation - United States Coast Guard "Development of a Centrigugal System for Separation of Oil and Solids from Shipboard Discharge Water", Report No. CG-D-118-75; July 1975

3. Department of Transportation - United States Coast Guard "Assembly and Testing of the Mark I Shipboard Separator System", Report No. CG-D-18-76; Dec. 1975

4. Department of Transportation - United States Coast Guard "Laboratory Evaluation of the Emulsifying Characteristics of Pumps", Report No. G-D-31-74; Oct. 1973

APPENDIX A - INITIAL OIL CONTROL PRESSURE DATA

The initial data for the oil control pressure is presented in Figures A-1 through A-3. These figures present oil control pressure for the 2-3/8 inch R. tap as functions of flow rate, flow distribution and inlet pressure for a rotational speed of 3600 rpm.

Figure A-1 plots the oil control pressure for the 2-3/8 inch R. tap versus flow rate for flow out the water and oil outlets and for zero psig inlet pressure. Figure A-2 plots the oil control pressure for the 2-3/8 inch R. tap versus flow rate out the water outlet for a 100 gpm total flow rate and a zero psig inlet pressure. Figure A-3 plots the oil control pressure for the 2-3/8 inch R. tap versus inlet pressure for a constant 100 gpm flow rate out the oil and water outlets.

Figure A-1 indicates that the oil control pressure remains constant if the flow is out of the oil discharge, but not if the flow is out of the water outlet. Flow friction in the oil discharge tube would show the reverse effect. We conclude that if there is no air bleed port in the shaft and not sufficient oil outlet flow to entrain air, that any inlet air accumulates in the rotor and results in a lower centrifugal head or pressure at the oil control port. The data for Figure A-1 was time-dependent; i.e., the total time of testing was cumulative with increasing flow rate.

Figure A-2 shows the same effect of air accumulation, independent of total flow rate and time. When most of the flow is out of the oil outlet and, hence, air is entrained out of the rotor, then oil control pressure remains high. With most of the flow out of the water outlet, air can accumulate and shift the oil control pressure lower.

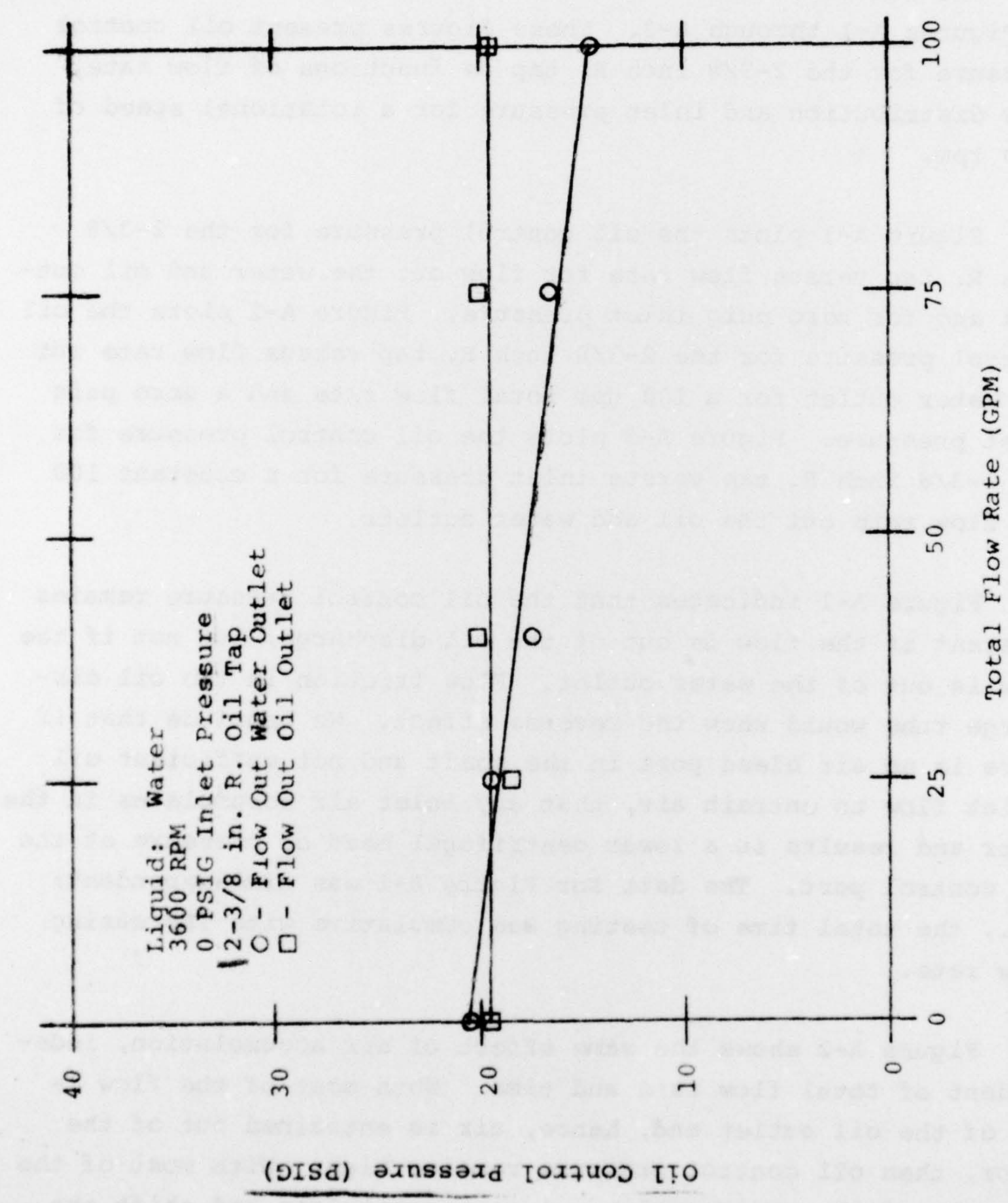

Figure A-1. Oil Control Pressures Versus Flow Rate

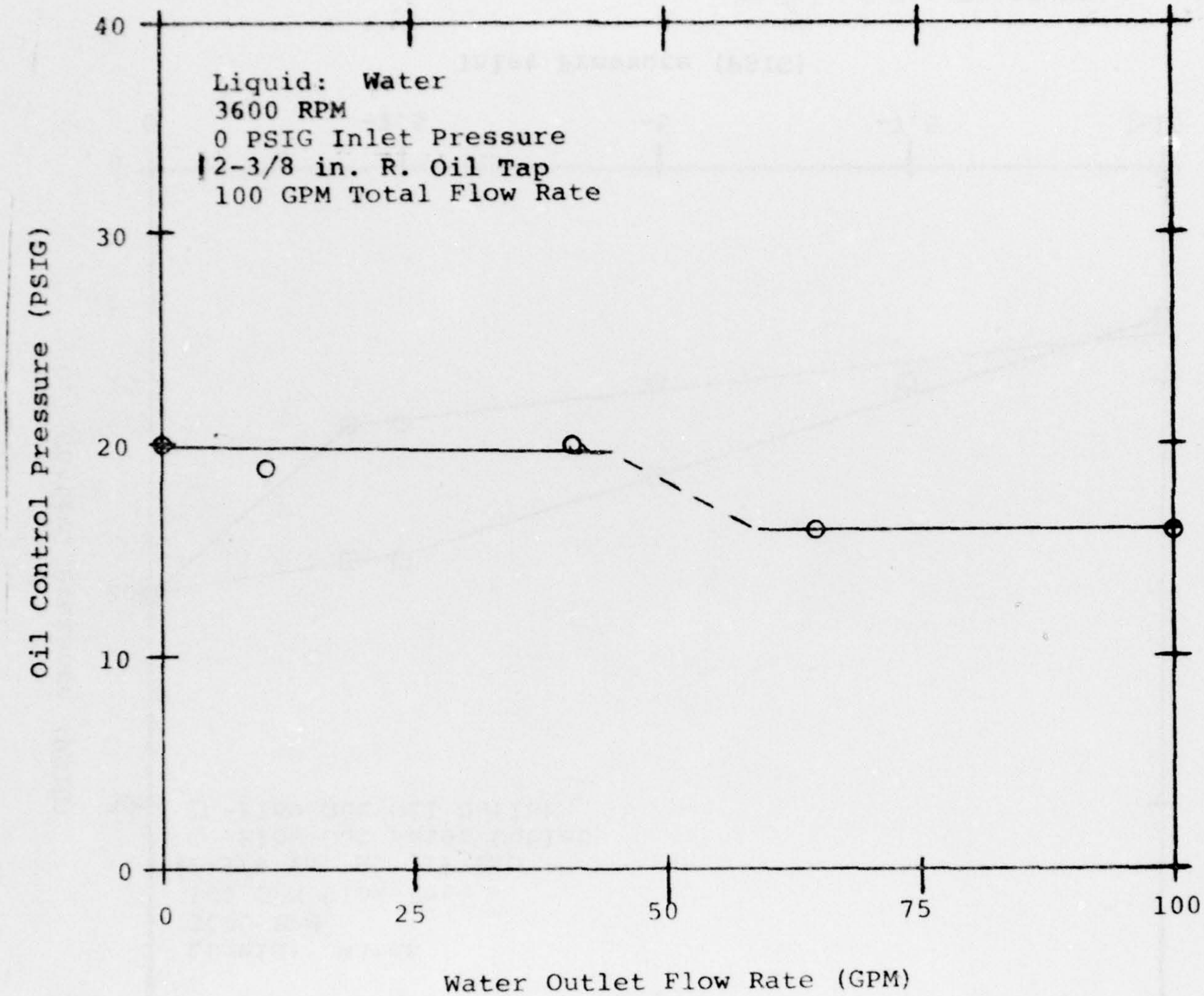

Figure A-2. Oil Control Pressures Versus Flow Distribution

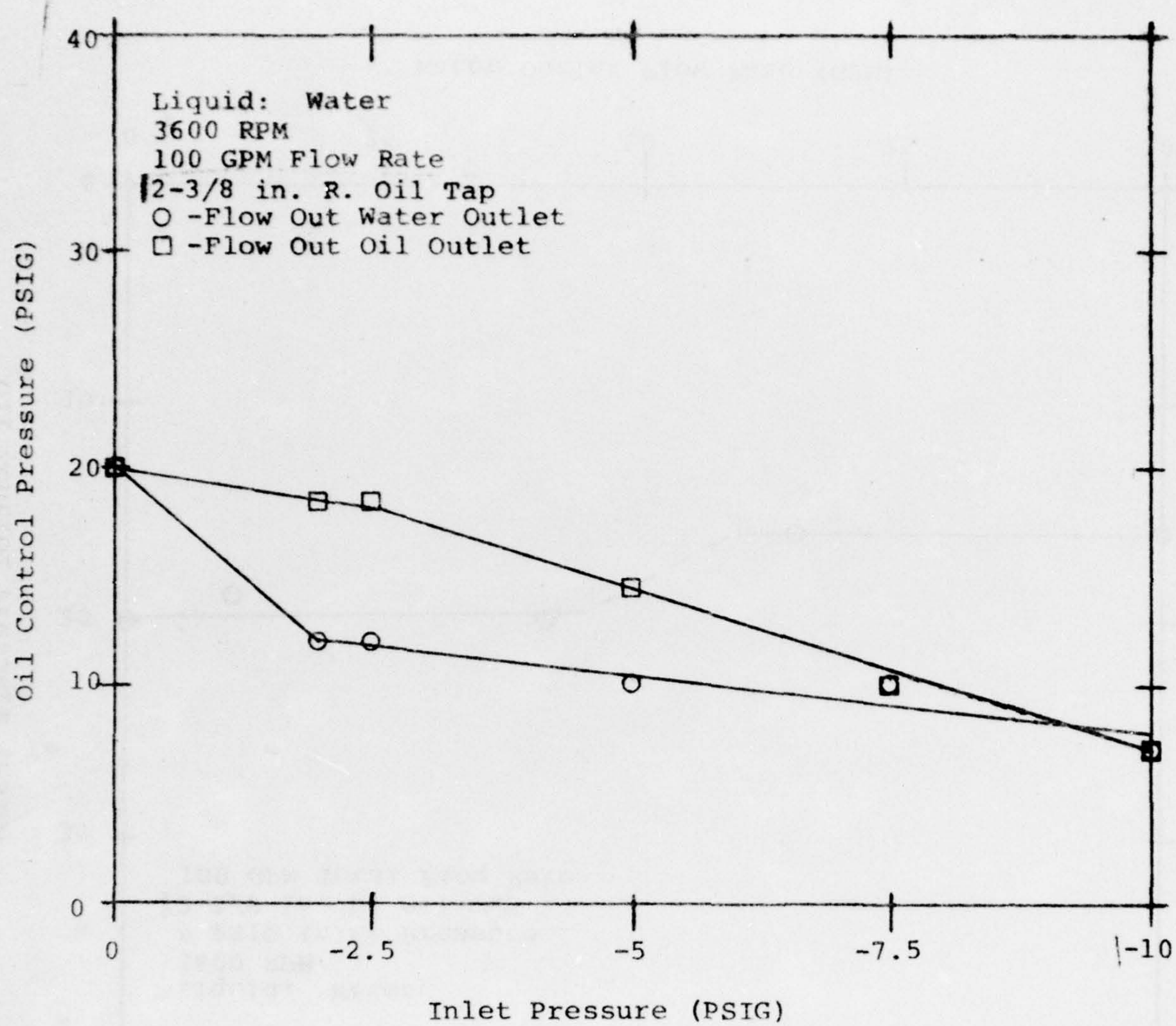

Figure A-3. Oil Control Pressures Versus Inlet Pressure

Figure A-3 shows the same effect even more strikingly, because with suction at the inlet, air is more likely to de-sorb and separate from the water in the rotor. At slight suction, oil outlet flow is able to carry this air out. At high suction, the air core in the rotor at equilibrium is large, and oil control pressure is low regardless of discharge flow.

In general, this data taken before the shaft air bleed was provided shows shifts of several psi in the oil control pressure. This does not compare well to the data taken later and reported in Section 4.5.